NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EFFICIENCY AND PRECISION EXPERIMENTATION FOR AUGMENTED REALITY CUED MAINTENANCE ACTIONS

by

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June 2018

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2018	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE
EFFICIENCY AND PRECISION EXPERIMENTATION FOR AUGMENTED REALITY CUED MAINTENANCE ACTIONS

5. FUNDING NUMBERS

6. AUTHOR(S) Christopher J. Angelopoulos

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

The Department of Defense (DoD) and commercial industry expend significant resources to recover from failed maintenance actions. One known factor is the strained communication link connecting designers to maintenance professionals. Current technology leverages the technical manual, in both paper and flat electronic form, for this link. Augmented reality (AR) offers the potential to mitigate this deleterious factor by maintaining or transforming information into a more palatable form. This research measured human precision and efficiency by comparing augmented reality cued (ARC) and traditionally cued (TC) maintenance procedures in five tasks designed to elicit absolute, cumulative, absolute referential, and complexity errors across both ARC and TC conditions. Results indicate ARC procedures are statistically more efficient for human precise placement tasks of small parts, while precision is roughly equal. The assembly task, analogous to an assembly procedure, is statistically both more efficient and more precise using ARC versus TC procedures. ARC procedures for small part placement and assembly tasks are more efficient, faster, and in most cases at least as precise.

14. SUBJECT TERMS
augmented reality, human precision, human efficiency, maintenance

15. NUMBER OF PAGES
143

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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EFFICIENCY AND PRECISION EXPERIMENTATION FOR AUGMENTED REALITY CUED MAINTENANCE ACTIONS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MODELING, VIRTUAL ENVIRONMENTS, AND SIMULATION

from the

NAVAL POSTGRADUATE SCHOOL
June 2018

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ABSTRACT

The Department of Defense (DoD) and commercial industry expend significant resources to recover from failed maintenance actions. One known factor is the strained communication link connecting designers to maintenance professionals. Current technology leverages the technical manual, in both paper and flat electronic form, for this link. Augmented reality (AR) offers the potential to mitigate this deleterious factor by maintaining or transforming information into a more palatable form. This research measured human precision and efficiency by comparing augmented reality cued (ARC) and traditionally cued (TC) maintenance procedures in five tasks designed to elicit absolute, cumulative, absolute referential, and complexity errors across both ARC and TC conditions. Results indicate ARC procedures are statistically more efficient for human precise placement tasks of small parts, while precision is roughly equal. The assembly task, analogous to an assembly procedure, is statistically both more efficient and more precise using ARC versus TC procedures. ARC procedures for small part placement and assembly tasks are more efficient, faster, and in most cases at least as precise.

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ACKNOWLEDGMENTS

I would like to thank those who have been instrumental in the production of this research:

First and foremost is my family, and specifically my wife, Sarah, whose patience and support have been limitless. Without her, none of this is meaningful.

LtCol G. Roberts, NAVAIR PMA-257—team provided resourcing and access critical to timely execution. I am particularly thankful for your precision and drive that so aptly personifies a Marine.

Peter Squire and ONR Code 30—foundational resourcing for development was essential.

MOVES FutureTech—highly skilled development team was absolutely crucial to the success of this research. The team rapidly incorporated changes and provided valuable feedback.

Rabia Khan—her assistance doubled the experiment throughput and drastically reduced data extraction time.

3D Zephr Pro Team—free photogrammetry software helped the exploration phase of this research.

Dr. Rudy Darken and Perry McDowell—thank you for shaping the research and providing the latitude and resourcing to excel.

Naval Postgraduate School—a world-class education coupled with a warfighting vision focuses timely and meaningful research. Without the unique civilian/military setting, none of this research would be possible.

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I. INTRODUCTION

A. RELEVANCE

The foundation of this work does not expose a new problem, but rather one that has plagued all human activity since the dawn of time: communication. Our technological advances have outpaced our individual capacity to fully comprehend at a level of detail required to build, operate, and maintain assets. Our solution of professional specialization, while necessary, constructs significant fundamental informational barriers between our artists, designers, engineers, operators, and our maintainers. While the computer has vastly broadened and deepened human understanding, we have erroneously strived to teach humans how to communicate with a computer within its domain. Although critical in some fields, it is corrosive to many other professional endeavors. AR changes this dynamic, presenting information in a more palatable form.

One may envision, for example, the difficultly to program a robot with a camera to precisely place an object upon a table. The program must be able to:

- localize the robot within its environment
- identify the table within its greater environment
- describe the table and designate parts of the table for referencing
- identify the object of interest, differentiating it from other objects
- describe a method to place the object in the intended position

While conceptually simplistic, precision requires more information such as: object's orientation within the world and how the objects characteristics define its own orientation, placement of the object upon a specific table and table's differences from the standard table, measuring method and tools, calibration of the measuring equipment, and the validity of the current calibration. These examples highlight the potential for miscommunication between designers and maintainer.

B. EVOLUTION OF MAINTENANCE COMMUNICATION

While not linear by any means, we can summarize the progression of the designer to maintainer communication pathway. Conceptually, we can place milestones to mark its adaptations. In the past, inventor/owner/operators served as the foundation or cornerstone of technological innovation. The moment the inventor shared their invention necessitated clear and repeatable communication. How does one ensure others can build, operate, or maintain this technology without constant supervision? Enter apprenticeship, our first milestone. Inventors taught and trained, in the desire to address small-scale transfer of technology, a cadre of users and maintainers. As widespread deployment of technology scaled outside proximal access, apprenticeships become over burdensome. Written engineered procedures, the next marker, mitigated this deficiency to a great extent by transforming spatial tasks into verbal ones, while mass production symbiotically amplified its positive effect. Our last marker brings us to the electronic domain, where deployment of written procedures becomes cheap and accessible. As a general statement, this domain did not alter the format or method of displaying information to the maintainer. Technical manuals merely transitioned to electronic documents, where new search functionalities optimized work. One may click on a hyperlink and acquire requested information, in text, graphic, video, or audio form. The information does not know what the maintainer is working on, and cannot objectively facilitate proper quality controls, it is passive. The maintainer must know what they are maintaining, what, on this object, is different from original specification, and know the process of gathering validated and verified contextual maintenance information. Can AR disrupt this dynamic? It is time to place another milestone?

C. SHOULD DOD AND INDUSTRY TAKE NOTICE?

All Department of Defense (DoD) services acquire, operate, and maintain assets at significant taxpayer expense. Both DoD and industry span the entire spectrum from heavy manufacturing assembly to individualized repair services and individually desire operational superiority over competitors. A method to maintain or achieve operational superiority over a competitor leverages technology. This leveraging can, in turn, raise the minimum personnel requirements to operate and maintain assets. An increase in asset complexity creates secondary and tertiary cost ripples. Obviously, initial training requirements must be able to cover new technologies, but what about personnel currency training requirements? Do you need to add more personnel to perform the same amount of maintenance? Do you need a better quality-assurance system? What about quality assurance training? Raw acquisition costs typically increase, as do refurbishment actions. Potentially, the reduced breadth of manufacturers able to produce the technology as well as limited procured assets, add risk. Costs have the potential to increase exponentially.

Typical systems contain significant cost drivers originating from operations and support (Jones, White, Ryan, & Ritschel, 2014). This is the origin of AR's return on investment. AR can present guided contextual information simplifying maintenance processes. This can potentially reduce error and system specific training tails at the same time increasing efficiency.

Most importantly, objectivity redefines the concept of maintenance communication. Instead of maintainers pulling designated information in a subjective way, computer vision coupled with object recognition can offload that communication stream to an objective push model. Information presented in this way, to the maintainer, is no longer passive, it provides immediate context. AR, in its fully matured form, can identify objects with the potential to:

- know the object you are working on, and with reach back, all changes to its original specification
- identify unknown or unverified changes made to an object
- provide real time contextual information, a set of tasks for the specific object under current scrutiny
- identify the proper tool, and observe its use
- know the order of removal or installation of parts
- know the current step of a procedure

- know a part is out of specification (broken)
- designate locations without traditional measurement tools
- gather raw data not processed through the human cognitive domain to ingest into logistic processes

The previous list is only a subset of AR's potential to redefine the communication pathway to a more objective one.

D. SCOPE OF EFFORT AND THESIS ORGANIZATION

This thesis attempts to answer the following research question:

To what extent does augmented reality cueing affect efficiency and precision of maintenance tasks as compared to written forms of communication (e.g., technical publications)?

A counterbalanced experimental study using a pairwise comparison establishes the foundation for all analysis and conclusions. During the experiment, subjects performed a set of maintenance actions decomposed to an atomic level. Precision and efficiency are metrics of their performance. The difference between the locations of the subject's part from a known perfect position is precision, while task completion times coupled with precision assess efficiency. Subjects performed tasks under two conditions: TC communication (technical manual) and ARC communication (Microsoft HoloLens). The population of interest encompasses military and government (civilian) maintainers or assembly professionals.

1. Omitted Areas of Study

The state of AR commercial off the shelf platforms is not central to the discussion. Influences of a product in development on the assessment of precision and efficiency is important as Chapter IV expands.

The scoping of this thesis precluded a holistic look at AR's effect on all maintenance and assembly tasks. Chapter II bounds the research focus.

Evaluating a realistic maintenance task presents a multitude of issues. Many DoD maintenance procedures are too lengthy and do not present themselves in a way that facilitates scientific rigor. Confounding variables present significant assessment difficulties. For example, if there are only four bolts to remove the subject may intuitively progress through the task. Acquiring military parts pose resourcing, complexity, and in some cases classification restrictions. Availability and cost of useable military parts complex enough to enable scientific rigor is prohibitive.

Although enabling symbiotic technologies for AR, computer vision and object recognition are deliberately minimized. Microsoft HoloLens headset integrated with Unity's Vuforia is the only object recognition used and is used to locate the fiducial marker (amplifying remarks Chapter III.E.3.b). Fiducial marker recognition aligns the virtual world within the real world. Experimental scoping constrained the use of computer vision and object recognition to reduce variability and possible confounds. Mirrored or high gloss surfaces present significant challenges for computer vision facilitated object recognition, for example.

This thesis is in no way a judgment of the Microsoft's HoloLens platform. Chapter III addresses the question of choosing an experimental platform.

2. Thesis Organization

The background presented in Chapter II, defines AR, presents a few examples of hands-free AR platforms and industry's use of them, examines similar research, and provides a broad overview task analysis for this experiment. Chapter III contains the approach which seeks to address questions expected of the reader while bounding the application of precision within four bins. Chapter III also describes study implementation and frames the experiment while simultaneously presenting limitations. Chapter IV, Results and Analysis, explains the process of extracting precision and efficiency data and presents the raw results. Chapter V affords interpretation while Chapter VI concludes with implications and future work.

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II. BACKGROUND

A. AR DEFINED

As in many fields distilling a concrete, encompassing, precise and yet generalized definition for augmented reality (AR) is difficult. Two definitions give an introduction into AR's domain. Milgram, Takemura, Utsumi, and Kishino (1994) place AR along a spectrum where one end is the physical world and the other is completely virtual. The authors coined the term Reality-Virtuality (RV) encompassing the entire spectrum depicted in Figure 1.

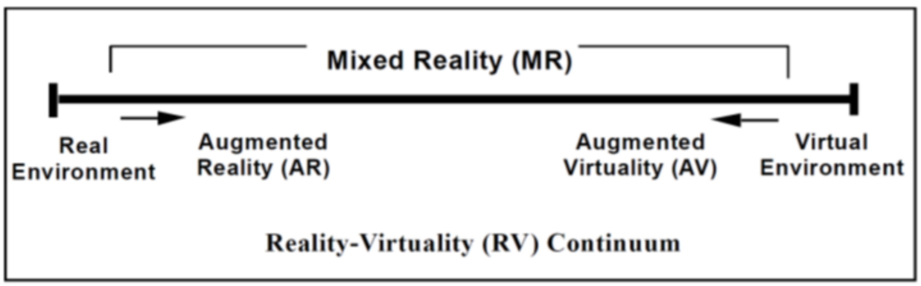

Figure 1. RV Continuum. Source: Milgram et al. (1994)

Milgram et al. (1994) further characterize AR as "augmenting natural feedback to the operator with simulated cues" (p. 284). Azuma (1997), in his seminal work, defines AR as possessing three essential conditions: a leveraging of both the virtual world and the real world, operation in real time to include user input and output, and three dimensional alignment of the virtual within the real world. These definitions are foundational to this thesis' experiment where subjects leverage simulated cues to precisely orient real objects within the real world.

B. A SUMMARY OF HANDS-FREE AR PLATFORMS

Carmigniani, Furht, Anisetti, Ceravolo, Damiani, and Ivokoic (2011) propose a taxonomy of AR displays. Scoped effort for this research focused on user specific augmentation and hand-free platforms, which precluded any augmentation projected directly onto real objects. Table 1. is extracted from Carmigniani et al.'s taxonomy.

Table 1. Advantages and Disadvantages of AR HMD.
Source: Carmigniani et al. (2011)

Type of Display	HMD	
Techniques	Video-see-though	Optical-see-through
Advantages	Complete visualization control, possible synchronization of the virtual and real environment	Employs a half-silver mirror technology, more natural perception of the real environment
Disadvantages	Requires user to wear cameras on his/her head, requires processing of cameras video stream, unnatural perception of the real environment	Time lag, jittering of the virtual image

In this research, we focus on hands-free activity and offer a brief glimpse into current industry efforts within the head mounted display subdomain of AR. The chosen platform is Microsoft HoloLens, a head mounted product that maps the entire physical environment to better affix virtual objects or holograms within (Microsoft, n.d.). The Microsoft team included spatial audio along with voice and gesture inputs that enable hands free operation. Magic Leap is another full throated AR platform leveraging light field technology, object recognition, audio, and inputs for voice, eye tracking, head direction, and gestures (“Magic in the Making,” n.d.). Epson produces a head mounted display with 1GB RAM, 8GB of storage, 6 hours of battery life, various sensors including GPS and a 5 megapixel camera (“Augmented Reality and Mixed Reality,” n.d.). DAQRI smart glasses uses 64GB storage, AR tracking and depth sensors as well as audio, with a 5800mAh battery (“DAQRI Smart Glasses,” n.d.). ODG most recent smart glasses, the R-9, have dual 1080p displays, and dual 5MP stereoscopic and AR tracking cameras (“ODG Compare Products,” n.d.). Glass takes a minimalist approach presenting monocular information to aid assembly or production (“Glass,” n.d.). Vuzix Blade smart glasses have an 8MP 1080p camera, audio and additional vibration notification ("Augmented Reality (AR) Smart Glasses for the Enterprise," n.d.).

C. AR IN MAINTENANCE OR ASSEMBLY

For many years academia and the scientific community pushed AR down the path from concept to scientific endeavor. As with any technology, maturation of both core and enabling technologies allowed industry to transform concept into application. A few examples of AR applications elicit enough understanding of the domain even though many companies have AR products in development. GE Aviation in 2017 piloted an effort combining Glass Enterprise Edition, Upskill's software package and Atlas Copco's torque wrench to evaluate mechanics' performance ("GE Aviation Successfully Augmented Reality in Maintenance," 2017). GE also evaluated wind turbine technicians within this environment. Both cases improved efficiency. Boeing ("Boeing Tests Augmented Reality in the Factory," 2018) recognized the advantages of Microsoft HoloLens enabled factory floor assembly procedures inducing a "90% improvement in first time quality" (para. 3) while simultaneously saving 30% of time. Additionally, the company tested wire harness assembly with Glass producing a 25% reduction in completion time while minimizing error (Sacco, 2016, para. 23). Abraham and Annunziata (2017, para. 10) analyzed the current manufacturing manpower situation with respect to gaps. They contend this technology, though various evaluations, enhances output by 32%.

D. SIMILAR RESEARCH

A Boeing team, circa 1992, produced four research applications featuring manufacture and maintenance activities highlighting both strengths and weaknesses (Caudell & Mizell, 1992). The authors communicate their endeavor to produce a "heads-up, see-through, head-mounted display (HUDSET)" (p. 659) where users can facilitate work through augmented cued procedures. Although the authors' AR definition does not line up precisely with Milgram et al. (1994) or Azuma (1997), they capture the core ideas of AR.

Tang, Owen, Biocca, and Mou (2003) evaluated the performance of 75 undergraduate university students spread equally through 4 treatments: a manual, instructions on a flat display, instructions on a display worn on the head, and AR. Measurements comprised perceived mental workload, speed, and precision in the assembly of Duplo blocks. The authors depict Figure 2. to express group average error, illustrating the dramatic benefits of registered AR for precision.

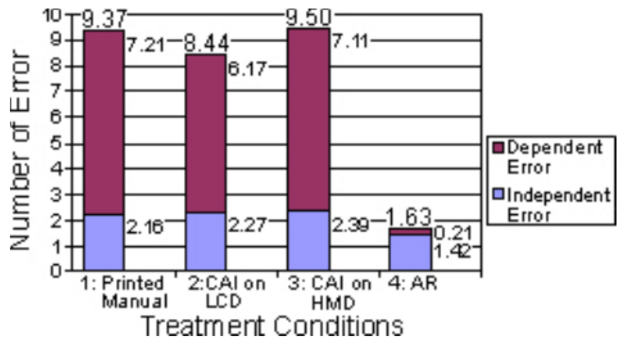

Figure 2. Average Error. Source: Tang et al. (2003)

Tang et al. (2003) focused on an assembly task where only discrete error is possible, because Duplo blocks only connect in a finite number of ways. Figure 3. illustrates the time advantage AR has over a printed manual.

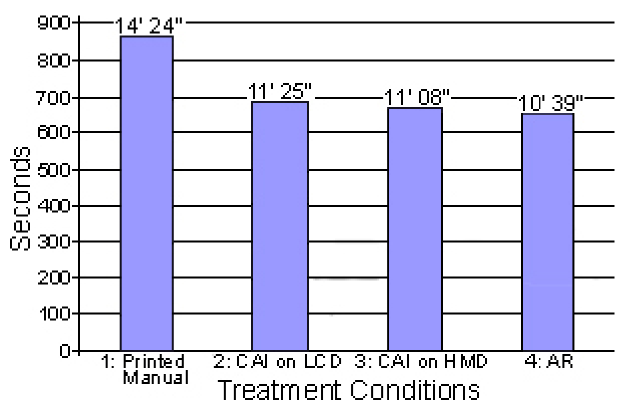

Figure 3. Completion Time (Average). Source: Tang et al. (2003)

While Tang et al. (2003) state their hypothesis that AR has a time advantage over other conditions is not supported, and conclude that the printed manual condition is significantly slower than all other conditions.

Henderson and Feiner (2011) conducted a user study of military mechanics for an AR application with a comparison to text based instruction via an LCD display and a heads up display. The authors indicated AR correctly directed attention on task faster than the traditional method of LCD display.

E. TASK ANALYSIS FOR ARC AND TC TASKS WITHIN EXPERIMENT

It is important to frame the scope of the tasks the subjects performed within the experiment. This thesis is not a grand statement on all maintenance activities. The following analysis is as a mechanism to frame the results. It uses the Department of Labor's granular list of knowledge, skills, and abilities, etc., published on the O*NET's website, from which most tasks can be broken down ("Browse by O*NET Data," n.d.). This thesis breaks the experimental tasks down into subtasks which are definable by the items on this list. This analysis uses abbreviated categories from this list, such as "CA5," defined as "Cognitive Ability 5: Memorization". Appendix F contains the entire list of descriptions.

1. ARC Task Decomposition for Cumulative Error Task in Experiment

The following is a list of steps required and their associated task requirements. Although this list is from the designed task, some subjects innovated and altered the procedure in various ways. Some grabbed all parts, placing one at a time, while one placed two at a time. The task is to place a small part in the workspace in position quickly and precisely.

1. Start task - Say "begin": CA5, CA10

2. Read instructions: CA1, CA3, CA5, SA1, SA2

3. Understand instructions: BS1, BS3

4. Grab part: CA2, CA5, PHA2, PSA1, PSA2, SA1, SA2

5. Place part on paper: CA2, PHA2, PSA2, SA1, SA2

6. Rotate part: CA8, CA9, PHA1, PSA1, SA1, SA2, TS1

7. Translate part: CA8, CA9, PHA1, PSA1, SA1, SA2, TS1

8. Repeat step 2 to 6 4 more times

9. Complete task / Say “complete”: CA5, CA10

2. TC Task Decomposition for Cumulative Error Task in Experiment

The following is a list of steps required and their associated task requirements. Although this list is from the designed task for the experiment, some subjects did not follow the procedure in various ways. Some only looked at the picture (did not have to understand text), some did not grab pencil, some measured all vertical measurements first, some measured all horizontal measurements first, some measured both before placing parts, and some did not even mark the paper workspace. The task is to place a small part in the workspace in position quickly and precisely.

1. Say “begin”: CA5, CA10

2. Turn page: CA2, CA3, PHA1, PSA1, PSA2, SA1, SA2

3. Read manual: CA1, CA3, CA5, SA1, SA2

4. Understand instructions: BS1, BS3

5. Understand measurement: BS1, BS3, CA6

6. Grab pencil and ruler: CA2, CA3, PHA1, PSA2, PSA3, SA1, SA2

7. Measure Horizontal for 1st part: CA2, CA3, CA4, CA5, CA6, CA7, CA8, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1

8. Mark paper for 1st part: CA2, CA3, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1

9. Measure Vertical for 1st part: CA2, CA3, CA4, CA5, CA6, CA7, CA8, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1

10. Mark paper for 1st part: CA2, CA3, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1

11. Drop pencil and ruler: CA2, PHA1, PSA2, SA1, SA2
12. Grab part: CA2, CA5, PHA2, PSA1, PSA2, SA1, SA2
13. Place part on paper: CA2, PHA2, PSA2, SA1, SA2
14. Rotate part: CA8, CA9, PHA1, PSA1, SA1, SA2, TS1
15. Translate part: CA8, CA9, PHA1, PSA1, SA1, SA2, TS1
16. Repeat 3 to 15 four more times
17. Complete task / Say “complete”: CA5, CA10

Table 2. on the following page, depicts the differences between the two conditions for the cumulative error task. Salmon color highlights a step, with the associated coded abilities or skills, only one condition requires. Green highlights steps that are identical across conditions. Yellow highlights a difference in scope, while purple highlights the steps that would need a much deeper analysis to expose more fundamental differences.

Table 2. Differences between ARC and TC Procedures for Cumulative Error Task in Experiment

Augmented Reality Cued	**Traditionally Cued**
1) Start Task/Say "begin"	1) Start Task/Say "begin"
	2) Turn page: CA2, CA3, PHA1, PSA1, PSA2, SA1, SA2
	3) Read manual: PHA1, PSA1, PSA2
2) Understand instructions	4) Understand instructions
	5) Understand measurements: BS1, BS3, CA6
	6) Grab pencil and ruler: CA2, CA3, PHA1, PSA2, PSA3, SA1, SA2
	7) Measure horizontal for 1st part: CA2, CA3, CA4, CA5, CA6, CA7, CA8, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1
	8) Mark paper for 1st part: CA2, CA3, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1
	9) Measure vertical for 1st part: CA2, CA3, CA4, CA5, CA6, CA7, CA8, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1
	10) Mark paper for 1st part: CA2, CA3, CA9, PHA1, PSA1, PSA2, PSA3, SA1, SA2, BS2, TS1
	11) Drop pencil and ruler: CA2, PHA1, PSA2, SA1, SA2
3) Grab part	12) Grab part
4) Place part on paper	13) Place part on paper
5) Rotate part	14) Rotate part
6) Translate part	15) Translate part
7) Repeat steps 2 to 6 four more times	16) Repeat steps 3 to 15 four more times
8) Complete Task / Say "Complete"	17) Complete Task / Say "Complete"

CAx: Cognitive Ability, PHAx: Physical Ability, PSAx: Psychomotor Ability, SAx: Sensory Ability, BSx: Basic Skills, TSx: Technical Skills

Only 43 required steps complete the entire task under the ARC condition, while the TC condition requires 69. From this alone, we can infer that the TC condition will take longer. This does not fully describe, with enough granularity, efficiency and precision differences observed between the two conditions. A more meaningful decomposition may expose elemental contrasts within the purple highlighted areas of Table 1. Understanding how to put a physical part within a virtual 2D wire mesh, for example, requires a different set of skills, knowledge, and abilities than reading a graphically enhanced technical manual. Armed with this analysis, we could potentially connect ARC’s efficiency and precision characteristics with the medium’s ability to communicate spatial information directly to the user in its most palatable form.

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III. APPROACH

A. WHY COMPARE ARC TO TC?

Foremost, AR is a dramatic change to the communication pathway between designer and maintainer. Arguably, virtual reality poses similar communication improvements, yet VR appears significantly constrained to the training environment. AR affords the opportunity to inject information into the operational environment, or during real time execution of procedures on physical equipment. Figure 4. describes usefulness of the medium versus proximity to the work environment. The post work environment focuses on aspects of quality assurance, performance assessment, and review.

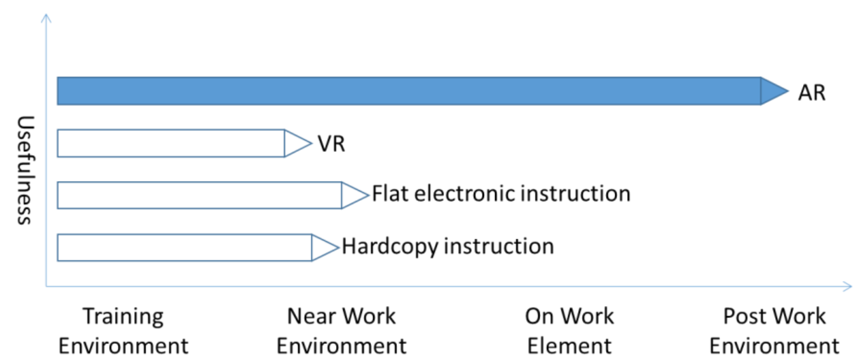

Figure 4. AR VR and Technical Manual Usefulness Comparison.

With this in mind, AR has the potential to reduce training requirements while improving quality of performance. The impact of this technology inject will influence how and what type of accession training, workforce strength and proficiency, and the maintenance and assembly processes themselves. The fact that AR allows personnel with less training and experience to perform at or near the level of better trained or more experienced person has the potential to significantly disrupt a wide range of jobs and industries.

TC maintenance procedures dominate the entire maintenance domain across the DoD. Systems designed many years ago transitioned from paper format to a flat or semiflat electronic format. Leading-edge system deployments do not appear to embrace virtual reality or AR in a holistic manner.

With any maturing technology, AR is approaching a feasible and deployable state. Alongside sister technologies of computer vision, head tracking, and localization, AR presents significant promise in suppressing cost across the entire life cycle, as discussed in the introduction. Any new technology must be subject to strenuous scientific rigor paving the foundation for informed acquisition strategies.

Industry is leading AR system integration and acquisition across a wide spectrum of professional activity in corporations such as GE ("GE Aviation Successfully Augmented Reality in Maintenance," 2017) and Boeing ("Boeing Tests Augmented Reality in the Factory," 2018). Scientific rigor facilitates the justification for emerging technology acquisition, and ensures the DoD acquires the right tool for the right job at the right time.

B. WHY ERECTOR SET PARTS?

Erector set parts are cheap, replaceable, and available. This is in stark contrast to DoD parts that may contain hazardous material, classification, or acquisition barriers. Erector set parts also enable multiple levels and alterable complexity where DoD parts are typically as is.

Most importantly erector set parts enable extraction of continuous precision data. In contrast to the work done by Tang et al. (2003) where placement of physical objects are discrete, this experiment forces users to express precision in a continuous context.

C. WHY MICROSOFT HOLOLENS?

This AR platform is a member of a growing field of hands-free devices. From a maintainer's perspective, hands-free is essential to optimize productivity. The HoloLens has three factors that led to its selection as the platform for the experiment.

1. Maturity

Even though Microsoft HoloLens is still in development, it bears a fairly robust development suite leveraging Unity among others. A support structure and development forum exist online.

2. Availability

Commercial enterprises and government entities create applications for this platform. Specifically, the Naval Postgraduate School employs a cadre of developers who are readily accessible and skilled in AR and VR development.

3. Virtual Anchoring and Stabilization Technique

To establish a base to anchor all virtual images within the real world, this platform continuously scans and maps the environment. Using this map, one may then place virtual images within context to the environment. Internal techniques then stabilize objects anchored in this manner. Those techniques allow a user to leave and return to a workspace knowing their objects retained their real-world positioning. This platform is also capable of occlusion of virtual images by real objects, enhancing immersion. In contrast, other platforms who use computer vision only, must reacquire the anchor point and then replace the virtual object where it should be every time visual tracking is lost.

D. DEFINING PRECISION THROUGH OBSERVED ERROR

Maintenance tasks span a wide range of human activity, each lending its contribution to precision of a specific action. In this analysis, we examine the effect not the cause. We are less interested in the decomposition of human activity to place an object, but specifically interested in the resulting difference in precision arising from that human activity. Observation of offset from an ideal provides error expressed in absolute, cumulative, absolute referential and complexity terms. They represent a significant portion of the maintenance and assembly error spectrum applicable to this research.

1. Absolute Error

The design of task 1 facilitates the expression of absolute error, or difference from a known fixed physical reference. As the subjects complete the same exact task 5 times (each offset from 5 separate L shapes), we can extract an average. How does absolute error connect to maintenance/assembly tasks? Example: Mark a specific location (place an object, drill a hole). ARC and TC procedures produce absolute error. AR systems, even with perfect tracking may anchor the virtual world incorrectly, inducing a global positional error.

2. Cumulative Error

Task 2's design forces the subject to produce cumulative error, or error built upon error. While this task starts from a fixed reference, each successive placement references the placement of the last. Horizontal difference of the last piece from a known perfect location is the measured cumulative error. Grid production (pattern to drill holes) is an example where maintenance or assembly tasks connect to cumulative error. A computer can technically cannot produce this error, since all measurements reference one origin. Arguably, this is not exactly the case, where one may attribute drift in tracking, or even drift of the anchor, as methods for AR to produce cumulative error.

3. Absolute Referential Error

Task 3 asks the subject to place 5 objects a dissimilar offset from 5 L shapes. This activity forces the subject to reference their procedures to ensure correct placement. Every TC maintenance or assembly procedure forces professionals to understand information, memorize, transport to the work environment, recall, and execute the procedure. While this distance can vary from inches to hundreds of feet, a distance exists. This error results in both a positional difference (precision) and a time differential (efficiency).

4. Complexity Error

Tasks 4 and 5 seek to elicit both positional and time differences through a difficulty spectrum. Task 4 instructs subjects to place objects in a pattern. Task 4 separates itself from tasks 1 through 3 by increasing the separation from initial reference while complicating the tasks. This may induce interpretation errors. Positional differences, with respect to a perfect placement, express precision while a time comparison between conditions enables efficiency computations. Task 5 guides subjects through an assembly, step by step. Incorrect connections, parts, or placement assess as precision error as well as incorrect routing, direction, and looping of the wire.

Language in general, spoken or written, is a difficult medium to communicate various types of tasks. As complexity increases, both within process and task, individual interpretation has an opportunity to enter. Professionals could take short cuts due to procedural length, or use a better method because they believe they are more informed than the designer, or simply fail to adhere to procedure due to lack of understanding. All of these elicit interpretation and potential error.

E. EXPERIMENTAL DESIGN

After consent, a demographic survey gathered pertinent information about each subject. All subjects performed two task sets under two conditions. Subjects acquired subject numbers sequentially. Odd numbered subjects performed ARC then TC procedures with even numbered subjects receiving treatments in the opposite order. The first task set is comprised of 4 subtasks that require placement of “erector-set” parts. The second task set is an assembly task comprised of “erector-set” parts. One condition presents the subject with TC procedures and the other ARC procedures. A post-test survey gathered opinion data while video recorded objective data.

1. Experiment Setup

The following is a list of essential parts.

1. Microsoft HoloLens
2. Software: HoloLens Assembly Tester Software. Source: (Heine, Johnson, & Lee, personal communication, March 23, 2018)[1]

[1] The thesis author conceptualized and designed the software. The development team created the application.

3. “Erector set” parts: Meccano Maker System Tower Bridge

4. Video camera 1: Canon Vixia HF10

5. Video camera 2: Sony HDR-XR520

6. Video camera stand: AmazonBasic 60-inch lightweight Tripod with bag

7. Steel magnetic blackboard 18inches x 24inches

8. Ruler: Shinwa Stainless Steel rule H-101A 150mm (model 13005)

9. Protractor: GemRed 2 in 1 Digital angle ruler in 200mm length

10. Command strips: Picture hanging strips

11. Magnetic strip: 3M 300LSE

2. Tasks

Each subject performed the experiment at one of two nearly identical stations. The only difference between the two was the make of the camera used to record their actions.

Each subject conducted two task sets in each of the two counterbalanced conditions. As they performed the tasks, a video camera recorded their actions. Video examination determined time required to place parts, precision and correctness of their actions, as well as explaining any discrepancies or outliers in data. Figure 5 depicts an experimental station.

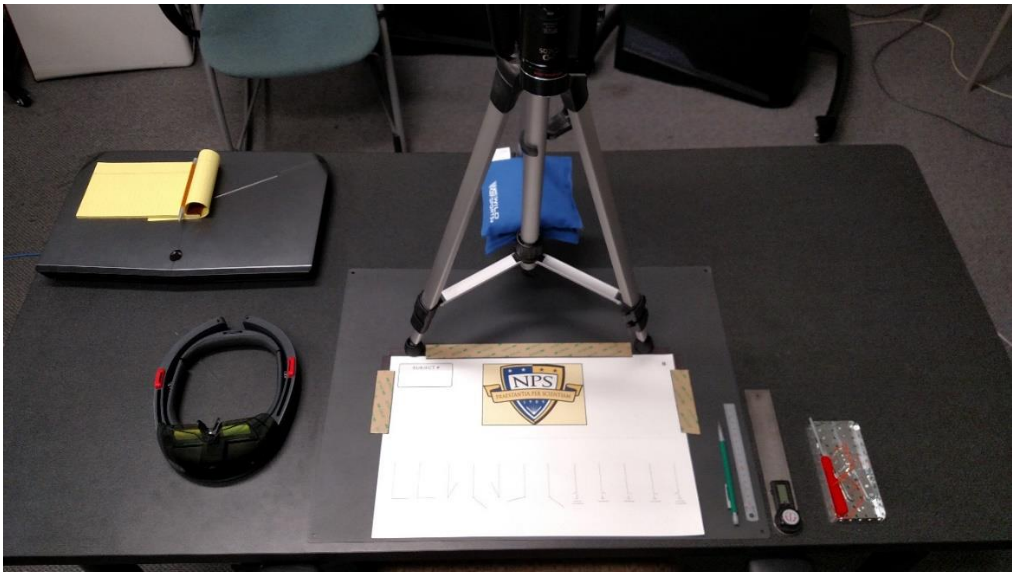

Figure 5. An Experimental Station

a. First Task Set

Task 1 (absolute error) has the subject place 5 identical erector set parts a set distance from 5 L shapes on a paper within their workspace (Appendices A, B and G).

Task 2 (cumulative error) has the subject place 5 identical erector set parts a distance from one L shape on a paper within their workspace (Appendices A, B and G).

Task 3 (referential absolute error) has the subject place 5 identical erector set parts a distance from 5 L shapes on a paper within their workspace (Appendices A, B and G).

Task 4 (complexity error) has the subject place 3 difference erector set parts in a pattern on a paper within their workspace (Appendices A, B and G).

b. Second Task Set

Task 5 (complexity error) has the subject assemble a larger object out of erector set parts and a wire (Appendix A).

3. Conditions

Subjects completed both traditional cued and augmented reality cued procedures during the experiment.

a. Traditionally Cued

This condition seeks to replicate the traditional method that many maintainers and assembly professionals work with: a technical manual. Text and graphics present information to the user. A manual created for the experiment (Appendix A) approximates a DoD style technical manual and would be familiar to DoD maintenance professionals.

b. Augmented Reality Cued

The subjects observed virtual images via Microsoft HoloLens as visual guides to place the parts. The NPS logo anchored these virtual images on paper within their workspace (Appendices B and G). This anchoring provided the basis for a lightweight user interface and object placement. Spoken commands, or gestures facilitated task progression. As stated earlier, object recognition only anchored the virtual space within the real space once per task. It did not identify and classify each individual physical part.

F. LIMITATIONS

Various issues related to hardware and resourcing presented a less than optimal environment for this research.

1. The Platform

Microsoft HoloLens is currently in development, which means that it is not commercially available and can change at any time. Inherent to the design are a couple of factors that impact this thesis. 50cm is considered the minimum effective range for comfortable viewing for relatively static environments, with virtual objects being removed at least 30cm away from the user ("Hologram stability," n.d.). The website further states that the optimal working range is 2 meters (6.2ft). In this experiment, subjects are typically no farther than 55cm from the objects. Modifications to the HoloLens software displayed objects within 30cm by shifting the near clipping plane within the experiment's AR application.

Microsoft HoloLens can use a continuous mechanism to anchor holograms upon computer vision tracked real world objects. This method produces an image that could shift without user movement. While not a problem for large-scale activity, this slight movement is problematic in the assessment of precise placement of objects. The experiment helps resolve this issue by anchoring each individual task once into the real world and turning off continuous updates.

When AR systems anchor a 3D virtual world within the real world, a 6 degree of freedom global absolute error is born. Without future refinement this error will impact measurements pertaining to and placement of all virtual objects. Although AR systems traditionally can only present absolute error from anchoring, its drift would constitute cumulative error. Additionally, the uncorrected drift due to tracking errors, can likewise impact precision.

2. Subjects

Volunteers were subject to the following exclusion criteria:

- Subjects unable to train to an unsupervised level of ruler and protractor proficiency after a maximum of thirty minutes of personalized training
- Inability to see clearly without the use of reading glasses or bifocal/ cumulative corrective lenses (these corrections caused either a blurry real object and a well formed virtual image or vice versa)
- Monocular vision (due to stereoscopic effects).

3. Computer Vision

An extremely limited use of computer vision using object recognition anchors the environment. A fiducial marker, an NPS Logo, specifically aligns the virtual world within the real. The Vuforia software element within Unity is intentionally further limited to initial anchoring of each task only. This prevents a jittery object or drastic shifts of the object.

4. Population of Interest

The population of interest is government and military maintenance professionals or those who perform maintenance actions. For example, this would include pilots who perform minor maintenance actions in the performance of flying duties.

5. Video Cameras

Video cameras are the primary source for data extraction. With this medium, limitations spawning from fidelity, optical distortion, and multiple cameras arise.

a. Resolution

The video cameras used in the experiment have a resolution of 1920 x 1080. This resolution makes the measurements less accurate than a smartphone or a 4k camera, yet are good enough.

b. Camera Differences

Two video cameras produced data individually. Although the models differ, images bore the same resolution 1920 x 1080. A unique image distortion correction algorithm for each camera normalizes both optical workspaces for proper comparison.

c. Optical Distortion

Two issues arose relating to measuring true distances on images. First, fisheye effect bends the image further from the image's center. Second, non-orthogonal image capture distorts measurements, similar to how objects look smaller at greater distances. Individual camera distances are static for this experiment. Chapter IV.C.1 describes each correction.

6. Two Investigators

Based on throughput requirements, two investigators conducted the experiment. Knowing potential differences in presentation and emphasis could skew data, a script, shown in Appendix C, ensured conformity. Multiple training sessions reduced differences.

G. LIMITATIONS IN THE APPARATUS

Using two different cameras is not optimal. It should be evident, even with individual corrections for each camera, a single model is ideal. Each camera exhibited slightly different zero zoom magnification. Although corrected for, by translating computations to the real world using with two different pixel densities, it again is not optimal. Given that resolutions at 1920 x 1080 were adequate for measurements to the 0.1 of a millimeter, pixilation of the image added unnecessary ambiguity for determining measuring points. A video camera of much greater resolution would help resolve this issue.

The calibration process attempts to alter the stereoscopic presentation to ensure the user observes the virtual image at the expected depth. Improper calibration results in parallax error as the image is closer or farther away than the intended depth. It is unknown how the internal calibration algorithm incorporates user input to compute interpupillary distance. Interpupillary distance is a necessary component for HMDs to adjust to each individual. Apparent subjectivity within the calibration process adds variability. Constructing a rigid calibration box could have eliminated this variability.

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IV. RESULTS AND ANALYSIS

Acquired data is in two formats: survey and video recorded human performance data. Survey data parsed into an Excel spreadsheet enabled subjective analysis while video data processed through Adobe After Effects facilitated precision and efficiency data extraction.

A. BASELINING MEASUREMENT PROCESS

Knowing the virtual image presented to the subject is in its exact specified real-world position by design, is very important to isolate human error vice computer compounded human error.

The following is the process to ensure virtual images are in their intended real-world positions. The task's virtual guides presented to the subjects during the experiment overlaid upon the task's image created a simulated workspace. This workspace printed on 11x17 paper formed the basis for baseline assessment. Comparing this printout to the normal printout of the subject's workspace showed identical positioning and scale of all printed objects (NPS logo, L shapes, etc.). Real measurements of the L shapes (known to be 85mm high by 40mm) confirmed they are of identical length to the normal workspace sheets. Measurements with Adobe Photoshop then confirmed proper placement of virtual images within the real.

Appendix H depicts the images that enabled the confirmation of perfect virtual object placement, by design. This does not infer object recognition, virtual to real world anchoring, or the tracking system of Microsoft HoloLens is perfect.

B. OBTAINING EFFICIENCY DATA

Video recorded human performance data pulled into Adobe After Effects facilitated analysis down to the hundredths of a second. Each subject had two sets of timing data: ARC and TC.

Efficiency data is based on both timing and precision. In general, both longer completion times and more error are less optimal. More specifically, a smaller error for a given completion time reflects better performance as does a quicker completion time for a given error. Efficiency data should also express numerically that a very precise action that takes longer would be as optimal as a less precise action completed very quickly. A simple algorithm of precision data multiplied by timing data meets the desired conditions. Smaller efficiency values are therefore better than larger efficiency values. This algorithm keeps the data unbiased and not beholden to a specific job.

Different job requirements would alter this simple efficiency calculation. For example, a job that requires high precision and is less interested in completion times may increase the magnitude of influence for precision when calculating efficiency. A curve could represent this alteration giving increasing numeric importance to higher precision.

The following groupings specify the extraction of performance measurements for this experiment.

1. Tasks 1 through 3

Subjects say “begin” to start their tasks. This marks the zero time of the task. The last touch or correction to the last placement of the erector set parts marks the end time. The differential is completion time.

2. Task 4

Subjects say “begin” to start this task. This marks the zero time of the task. The last time pencil marks scribe positioning guides is the setup time. A measurement from the setup time to the last part’s touch is pure part placement time, while the total completion time is measured from “begin” to the last touch or correction.

3. Task 5

Based on the complexity of this object, the zero time is at the word “begin” and the completion time is the time of last correction.

C. OBTAINING PRECISION DATA

Examining the video of each subject determined the locations of the physical parts placed within their workspace. Aggregation of error from a known perfect position, measured in millimeters, is the precision data. Smaller results are more precise.

1. Image Correction

To achieve the required accuracy. it is essential to correct various image distortions originating from camera use. Both fisheye and non-orthogonality adjustments corrected image data sufficiently for proper data extraction.

a. Fisheye Effect

Adobe After Effects provides a function that corrects for camera fish eye image distortion. Focal length of the camera is a primary contributor to the correction. (Filter > Adaptive Wide Angle > Fisheye)

b. Non-orthogonality

An image generated from a non-orthogonally (lens axis not orthogonal to desired sample surface) placed camera produces a distorted image. Corrections are essential to ensure measurements based on the image are correct. Appendix D is a series of images validating the process.

Given that image distortion may be non-linear we would not want to adjust the entire image at once. First, take the original image (Appendix D, Figure 44.) and bound a smaller area to correct. Then distort the smaller area linearly (skew, distort, scale) to achieve a ratio that mirrors real space (known distances align). We know the L shape's vertical line is 85mm and the horizontal line is 40mm. Appropriately scaling Adobe Photoshop measuring tool, so that it understands what 40mm is, now brings our measurements to a real-world scale. In this case, 567 pixels on the computer screen represents 40mm in the real world. An erector set part placed 10mm to the right and 17.5mm above the L shape produced post-correction measurements of 9.84mm to the right (measured at the top), 9.84 to the right (measured at the bottom), and 17.46mm above the

L shape. The minor differences are well within the error of using a metric ruler and an image measuring tool, and not primarily attributed to the correction applied. Using this process, we prove that correcting non-orthogonality does not alter real world distances extracted from the corrected image.

2. Task 1

Two lines parallel with the horizontal portion of each L shape bisecting the center of each end hole of the erector set part and one vertical line parallel with the vertical portion of the L shape through the center of the bottom hole of the erector set part, become the measuring lines on the corrected sub-image. The measurement is from the inside of the L shape to the first pixel of the erector set along the measuring line. A summation of the two horizontal measurements gives the horizontal error, and the single vertical measurement is the vertical error. Absolute aggregation of each L shape's vertical and horizontal error represents the total positional error of that part. Adding these absolute aggregations presents the total positional error for this subject on this task.

3. Task 2

Two lines parallel with the horizontal portion of the L shape bisecting the center of the end hole of the far-right erector set part and one vertical line parallel with the vertical portion of the L shape through the center of the bottom hole of the far right erector set part, become the measuring lines. Aggregate error is the horizontal error measured along each horizontal line added with the vertical error along the vertical line.

4. Task 3

This task is identical to task 1 with the exception of differing perfect positions.

5. Task 4

Task 4 has subjects place three physical parts: a part that looks like a C, a long part, and a square part.

a. C Part Precision

Two perpendicular lines from the bottom line of the NPS logo to each bend of the C part that touches the workspace sheet, are guides for vertical error measurements. A measurement along each of these lines compared to the perfect placement's distance creates two error values. The distance from the far-right vertical line's intersection with the bottom of the NPS logo along the black line to the logo's center is the horizontal measurement. Comparison to the perfect placement's measurement creates the horizontal error. Aggregated vertical and horizontal error form a total positional error of the part.

b. Long Part and Square Part Precision

A nearly identical measurement process facilitates precision data extraction for these two parts. Vertical lines intersecting the center of the end holes of the long part establish the line of measure. The distance from the intersection of the NPS logo to the first pixel on the part along the vertical lines is the vertical position and its comparison to a perfect placement creates the error values. The distance from the far-left vertical line's intersection with the bottom of the NPS logo along the black line to the logo's center is the horizontal measurement. Comparison to the perfect placement's measurement creates the horizontal error. Aggregated vertical and horizontal error form a total positional error of the part. The square part's procedure is the same.

6. Task 5

Precision of this task expresses itself in in a binary way by misconnecting parts, missing parts, incorrect positioning of parts, incorrect direction of parts (bolts or wires), or misrouting of wires. The ARC task 5 has 54 possible correct actions: small bolt attachment point #1 (4 parts, one location, one direction), small bolt attachment #2 (4 parts, one location, one direction), C part (4 parts, one location, one direction), long bolt attachment (7 parts, one location, one direction), wire routing (27 possible correct actions of placement, direction, and looping). The TC task 5 has 52 possible correct actions: parts placement is identical to ARC, with only the wire routing possessing 2 less correct actions.

7. Validation of Precision Algorithm as a Metric

A universally acceptable method to determine precise placement is not possible due to inherent subjectivity of the measure. Multiple biases exist that influence evaluation of precision. For example, an individual could erroneously determine hole alignment is the primary factor for precision because a task they performed in the past required it. Measuring precision must be objective and not influenced by bias.

To resolve this problem, five people, who were not subjects in the study, ranked the precision of alignment of 5 physical shapes upon their virtual representation on a printed sheet of paper depicted within Appendix E. With this setup the consensus placed the fourth part from the left the most precise, then position 3, position 5, position 1, and finally position 2 as the least precise. The experiments' precision algorithm agreed with the ranking of the human evaluators.

D. RESULTS

The counterbalanced experiment produced paired data from 34 Marine maintenance personnel. 16 subjects performed TC then ARC procedures and 18 subjects performed the opposite. Video corruption of 100% of a subjects' ARC data has completely removed this one subject from paired analysis. This left the TC first group 16 subjects and the ARC first group 17 subjects. All analysis, histograms, and boxplots completed with JMP 13.1.0. Excel 2016 produced all graphs within this section.

All analyses, that required a significance level, used an alpha of 0.05 unless otherwise noted.

1. Efficiency Data

Efficiency is work at a cost. In this context, precision multiplied by completion time is the algorithm of choice to compute efficiency. Millimeters of error represent precision and seconds represent completion time.

a. Task 1 (Absolute Error)

Three subjects failed to complete the task, and one subject presented outlier data greater than three times interquartile range. This analysis did not include the subject, but Appendix I contains the original analysis with the subject's data. Figure 6 is a histogram and boxplot, and Figure 7 is a paired t test of the remaining differential efficiency data.

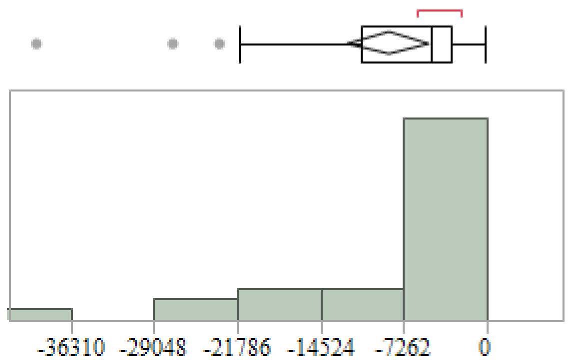

Figure 6. Histogram and boxplot of ARC minus TC Absolute Error Efficiency Data. ($\bar{x}_D = -8547.67$, $s_D = 9352.18$, $SE_D = 1736.64$, $95\%CI\left[-12105.04, -4990.287\right]$, $n = 29$)

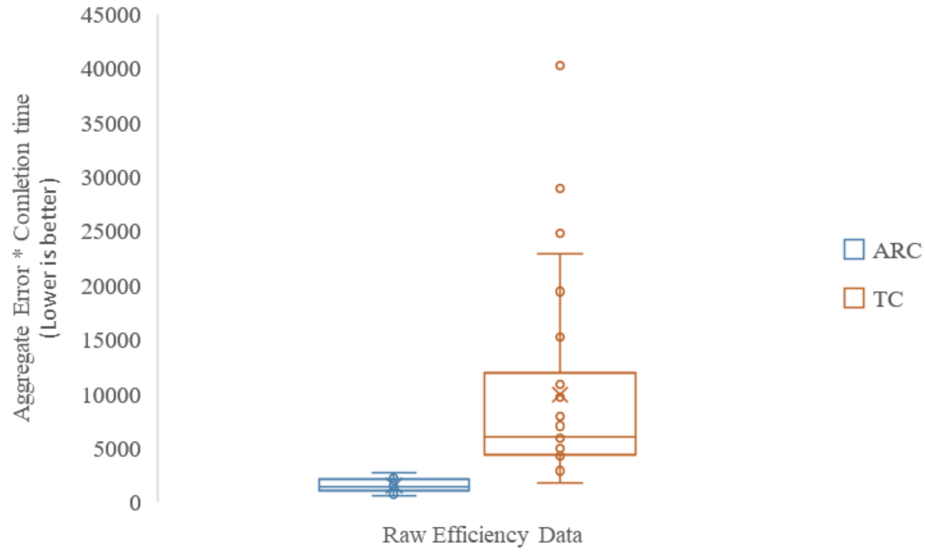

Figure 7. Raw ARC and TC Absolute Error Efficiency Data. Wilcoxon (TC minus ARC) results indicate that ARC is statistically more efficient than TC for absolute error (score $\bar{x}_D = 28.97$, $SE_D = 4.43$, $z = 6.53$, $p < 0.0001$, $95\% CI\left[4313.24, 10432.18\right]$).

b. Task 2 (Cumulative Error)

Figure 8 is a histogram and boxplot, and Figure 9 is a Wilcoxon analysis on each pair of the remaining differential efficiency data.

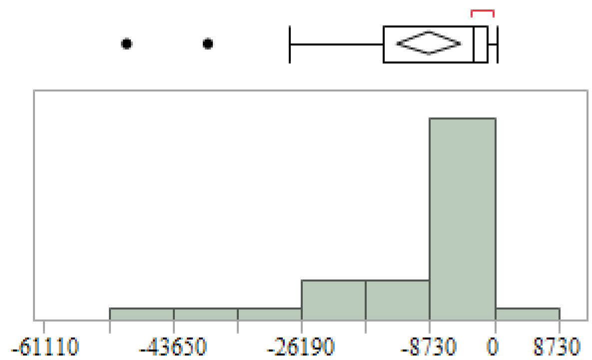

Figure 8. Histogram and Boxplot of ARC Minus TC Cumulative Error Efficiency Data ($\overline{x}_D = -8909.17$, $s_D = 12242.32$, $SE_D = 2131.11$, $95\% CI\left[-13250.1, -4568.23\right]$, $n = 33$)

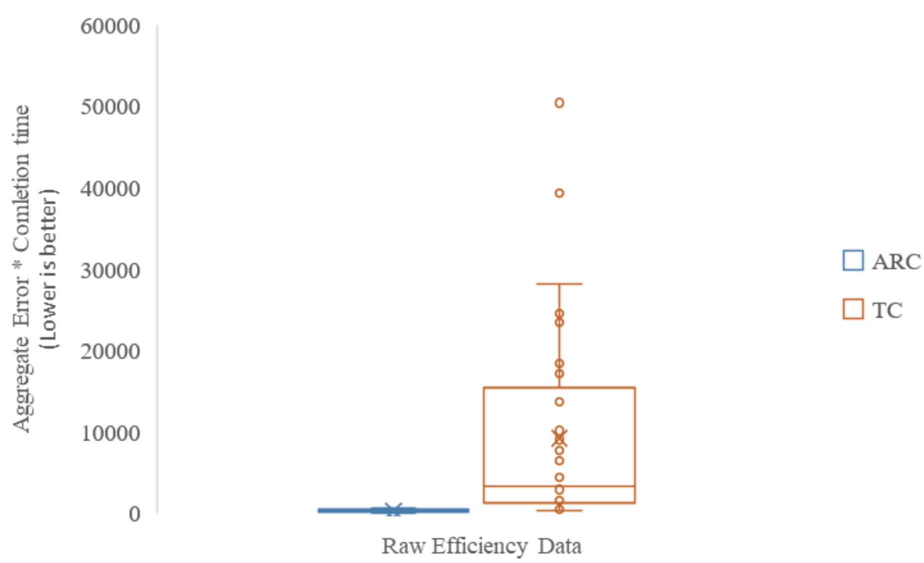

Figure 9. Raw ARC and TC Cumulative Error Efficiency Data. Wilcoxon (TC minus ARC) results indicate that ARC is statistically more efficient than TC for cumulative error (score $\overline{x}_D = 32.67$, $SE_D = 4.72$, $z = 6.91$, $p < 0.0001$, $95\% CI\left[3197.59, 9930.9\right]$)

c. Task 3 (Absolute Referential Error)

Two subjects presented outlier data greater than three times interquartile range. This analysis did not include the subjects, but Appendix I contains the original analysis with the subjects' data. Figure 10 is a histogram and boxplot, and Figure 11 is a Wilcoxon analysis on each pair of the remaining differential efficiency data.

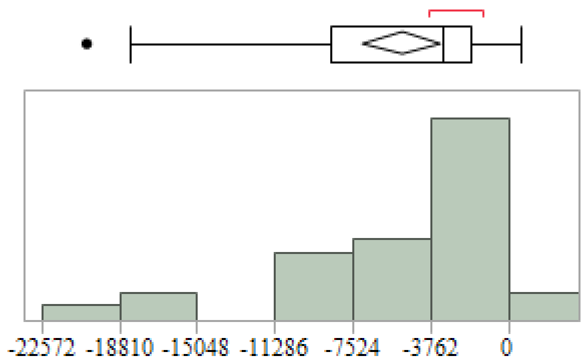

Figure 10. Histogram and Boxplot of ARC Minus TC Absolute Referential Error Efficiency Data ($\bar{x}_D = -5129.54$, $s_D = 5168.36$, $SE_D = 928.26$, $95\%CI\left[-7025.31, -3233.77\right]$, $n = 31$)

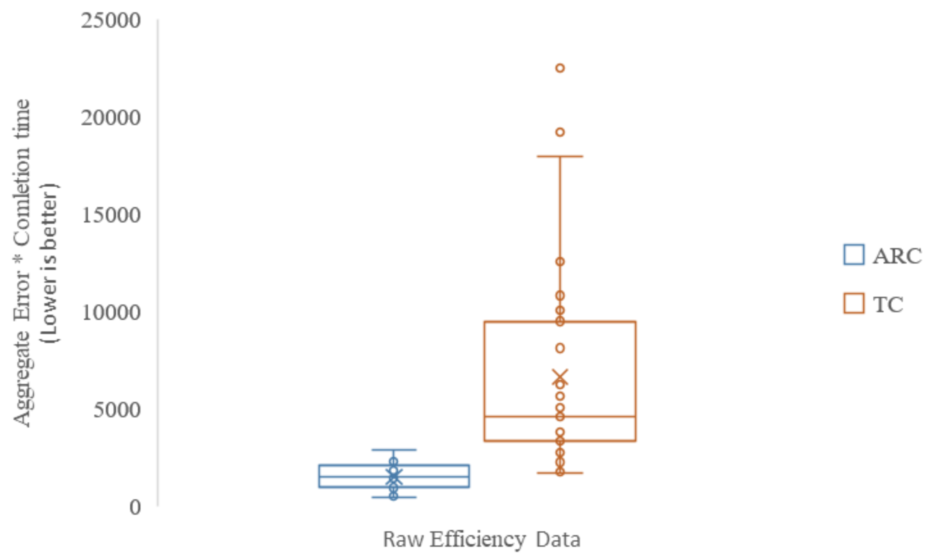

Figure 11. Raw ARC and TC Absolute Referential Error Efficiency Data. Wilcoxon (TC minus ARC) results indicate that ARC is statistically more efficient than TC (score $\bar{x}_D = 30.58$, $SE_D = 4.58$, $z = 6.67$, $p < 0.0001$, $95\% CI\left[3009.2, 5507.22\right]$).

d. Task 4 (Complexity Error)

This task had two time elements extracted: total completion and placement only. Placement only time references only the time it takes to place objects on guides the subject previously placed. Two subjects failed to complete the task.

(1) Total Completion

Four subjects presented outlier data greater than three times interquartile range. This analysis did not include the subjects, but Appendix I contains the original analysis with the subjects' data. Figure 12 is a histogram and boxplot, and Figure 13 is a paired t test of the remaining differential efficiency data.

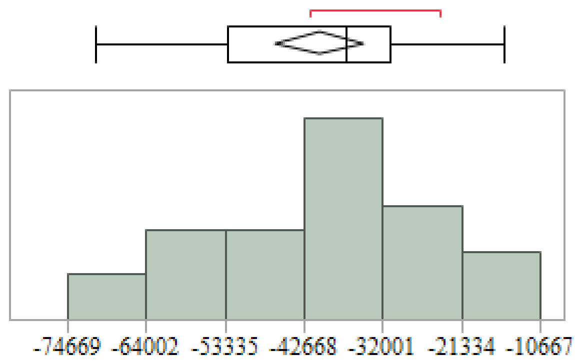

Figure 12. Histogram and Boxplot of ARC Minus TC Complexity Error Efficiency Data ($\bar{x}_D = -40608.15$, $s_D = 14995.14$, $SE_D = 2885.81$, $95\%CI\left[-40540.03, -34676.28\right]$, $n = 27$).

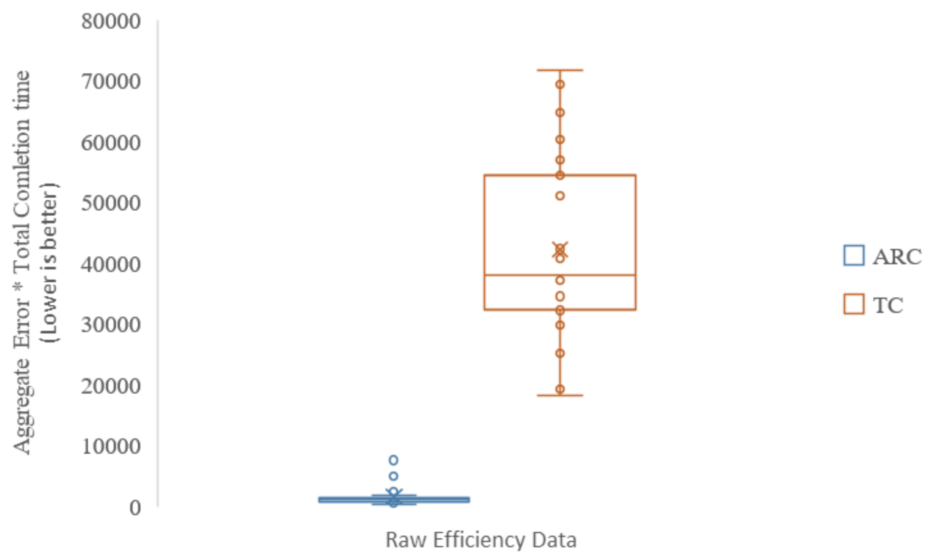

Figure 13. Raw ARC and TC Complexity Error Efficiency Data (Total Completion Times). Paired t test (TC minus ARC) results indicate that AR is statistically more efficient than TC ($\bar{x}_D = 40608.2$, $SE_D = 2885.8$, $t(26) = 14.07$, $p < 0.0001, 95\%CI\left[34676.28, 40540.03\right]$).

(2) Placement Only

One subject presented outlier data greater than three times interquartile range. This analysis did not include the subject, but Appendix I contains the original analysis with the subject's data. Figure 14 is a histogram and boxplot, and Figure 15 is a paired t test of the remaining differential efficiency data.

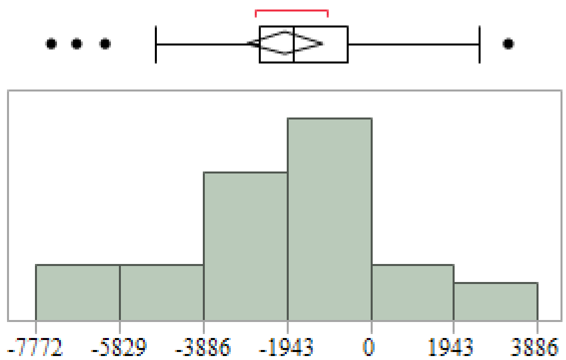

Figure 14. Histogram and Boxplot of ARC Minus TC Complexity Error Efficiency Data ($\bar{x}_D = -1968.22$, $s_D = 2397.94$, $SE_D = 437.8$, $95\%CI\left[-2863.63, -1072.81\right]$, $n = 30$).

Figure 15. Raw ARC and TC Complexity Error Efficiency Data (Placement Only Times). Paired t test (TC minus ARC) results indicate that AR is statistically more efficient than TC ($\bar{x}_D = 1968.22$, $SE_D = 437.8$, $t(29) = 4.4957$, $p < 0.0001$, $95\% CI\,[1072.81, 2863.63]$).

e. Task 5 (Assembly Complexity Error)

One subject failed to complete the task and the software failed during one subject's task. Figure 16 is a histogram and boxplot, and Figure 17 a paired t test of the remaining differential efficiency data.

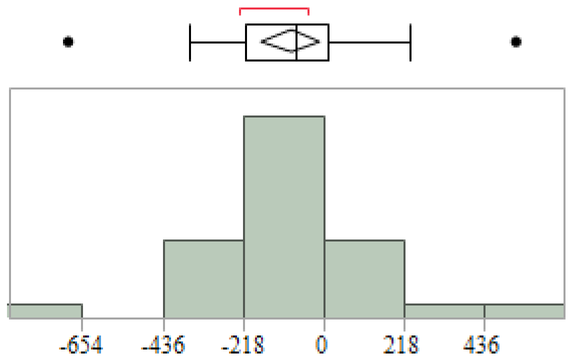

Figure 16. Histogram and Boxplot of ARC Minus TC Assembly Complexity Error Efficiency Data ($\bar{x}_D = -87.21$, $s_D = 215.21$, $SE_D = 38.65$, $95\%CI\left[-166.15, -8.26\right]$, $n = 31$).

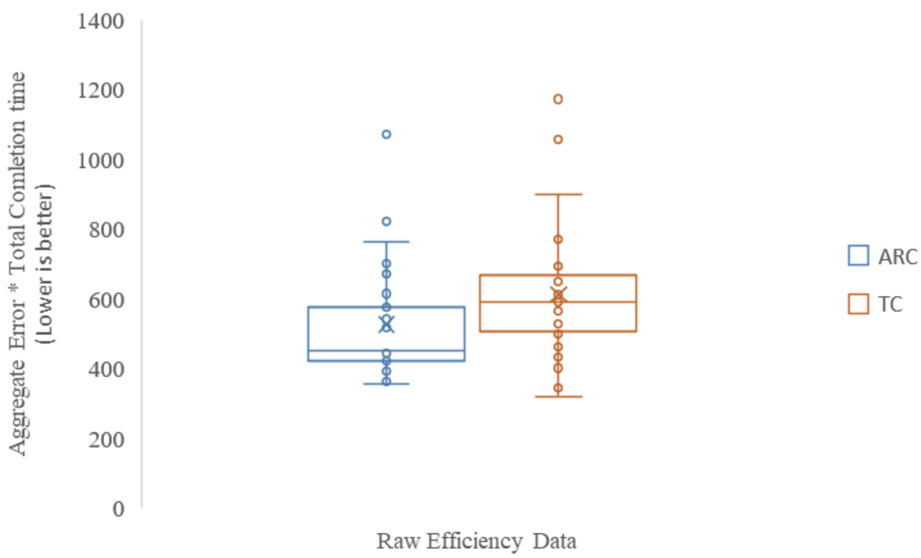

Figure 17. Raw ARC and TC Assembly Complexity Error Efficiency Data. Paired t test (TC minus ARC) results indicate that AR is statistically more efficient than TC ($\bar{x}_D = 87.21$, $SE_D = 38.65$, $t(30) = 2.26$, $p = 0.0315$, $95\%CI\left[8.264, 166.15\right]$).

2. Precision Data

Precision data is the aggregate error from a known perfect position along the horizontal and vertical axes.

a. Task 1 (Absolute Error)

Three subjects failed to complete the task and one subject presented outlier data greater than three times interquartile range. This analysis did not include the subject, but Appendix I contains the original analysis with the subjects' data. Figure 18 is a histogram and boxplot, and Figure 19 is a paired t test of the remaining differential precision data.

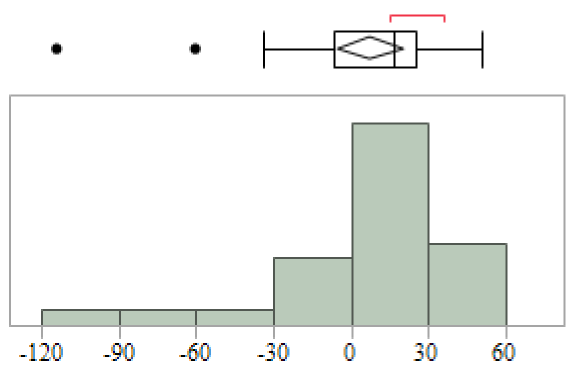

Figure 18. Histogram and Boxplot of ARC Minus TC Aggregate Absolute Error (mm) ($\bar{x}_D = 7.38$, $s_D = 33.77$, $SE_D = 6.27$, $95\% CI\left[-5.47, 20.22\right]$, $n = 29$).

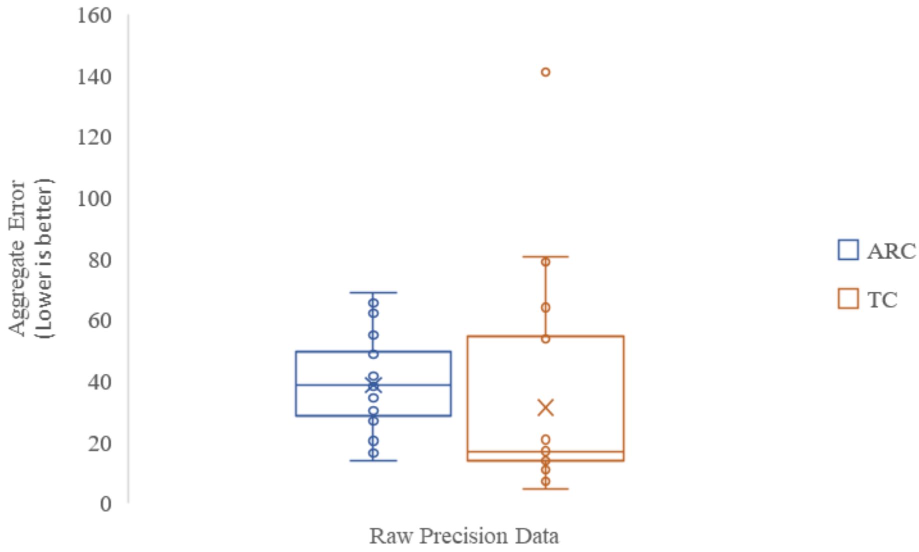

Figure 19. Raw ARC and TC Aggregate Absolute Error (mm). Paired t test (TC minus ARC) results indicate that AR is not statistically different than TC ($\bar{x}_D = -7.38$ $SE_D = 6.27$, $t(28) = -1.17$, $p = 0.249$, $95\%CI[-20.22, 5.47]$).

b. *Task 2 (Cumulative Error)*

Figure 20 is a histogram and boxplot, and Figure 21 is a Wilcoxon of each pair of the remaining differential precision data.

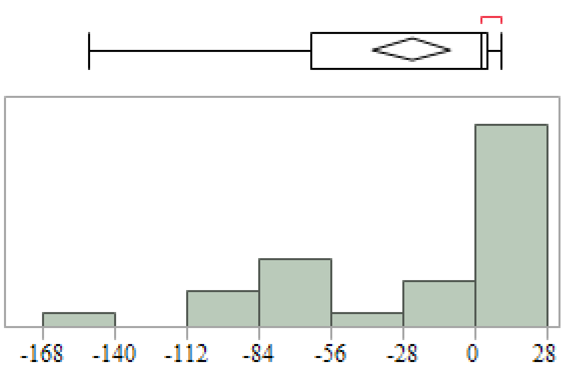

Figure 20. Histogram and Boxplot of ARC Minus TC Aggregate Cumulative Error (mm) ($\bar{x}_D = -24.53$, $s_D = 42.57$, $SE_D = 7.41$, $95\%CI[-39.63, -9.42]$, $n = 33$).

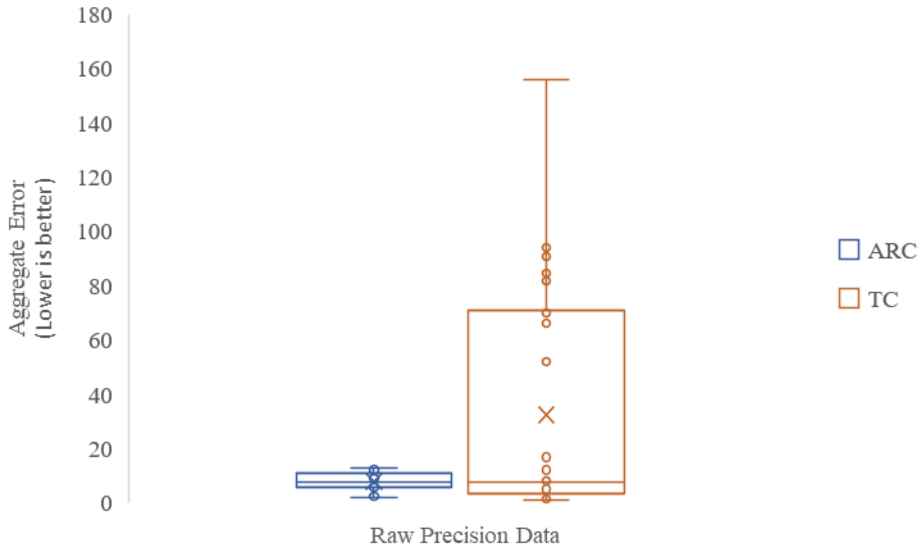

Figure 21. Raw ARC and TC Aggregate Cumulative Error (mm). Wilcoxon (TC minus ARC) results indicate that AR is not statistically different than TC (score $\overline{x}_D = 8.73$, $SE_D = 4.72$, $z = 1.85$, $p = 0.0648$, $95\% CI\left[-0.12, 34.2\right]$).

c. *Task 3 (Absolute Referential Error)*

Figure 22 is a histogram and boxplot, and Figure 23 is a paired t test of the remaining differential precision data.

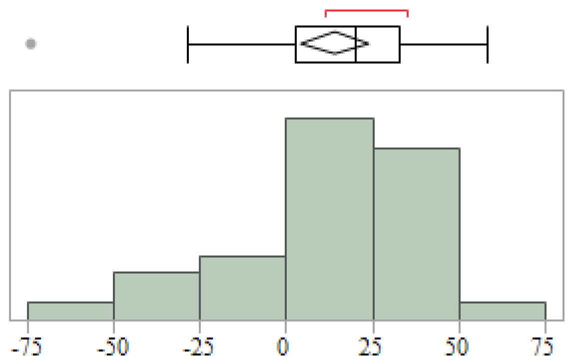

Figure 22. Histogram and Boxplot of ARC Minus TC Aggregate Absolute Referential Error (mm) ($\bar{x}_D = 14.21$, $s_D = 27.59$, $SE_D = 4.8$, $95\%CI[4.42, 23.99]$, $n = 33$).

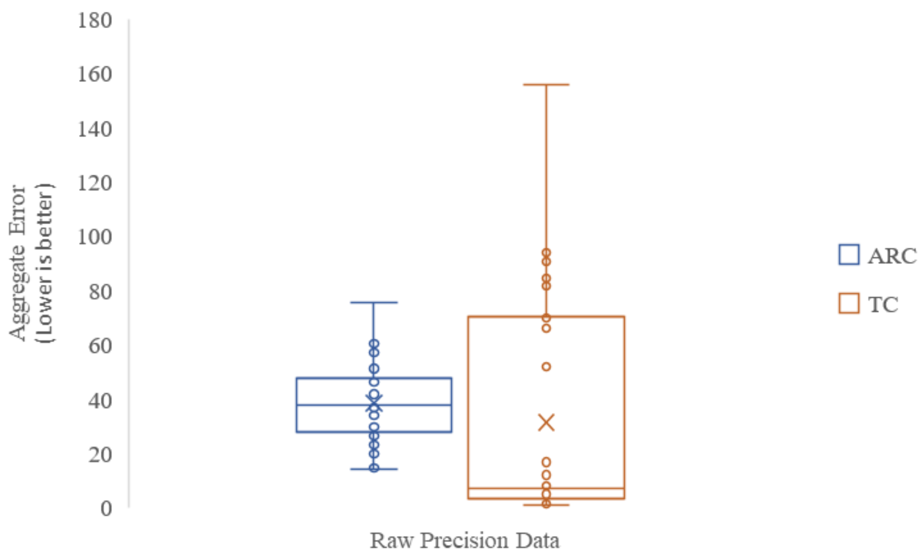

Figure 23. Raw ARC and TC Aggregate Absolute Referential Error (mm). Paired t test (TC minus ARC) results indicate that AR is statistically less precise than TC ($\bar{x}_D = -14.21$, $SE_D = 4.8$, $t(32) = -2.95$, $p = 0.0058$, $95\%CI[-23.99, -4.427]$).

d. Task 4 (Complexity Error)

Two subjects failed to complete the task. Figure 24 is a histogram and boxplot, and Figure 25 is a paired t test of the remaining differential precision data.

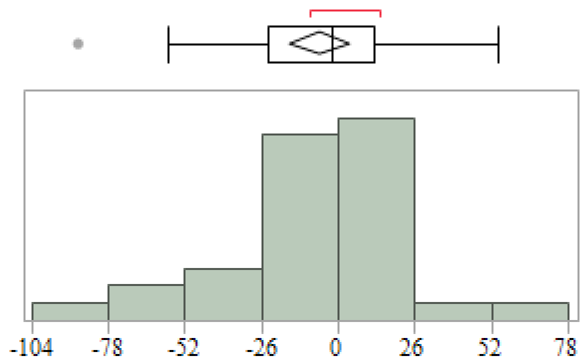

Figure 24. Histogram and Boxplot of ARC Minus TC Aggregate Complexity Error (mm) ($\bar{x}_D = -5.81$, $s_D = 27.93$, $SE_D = 5.02$, $95\% CI[-16.05, 4.43]$, $n = 31$).

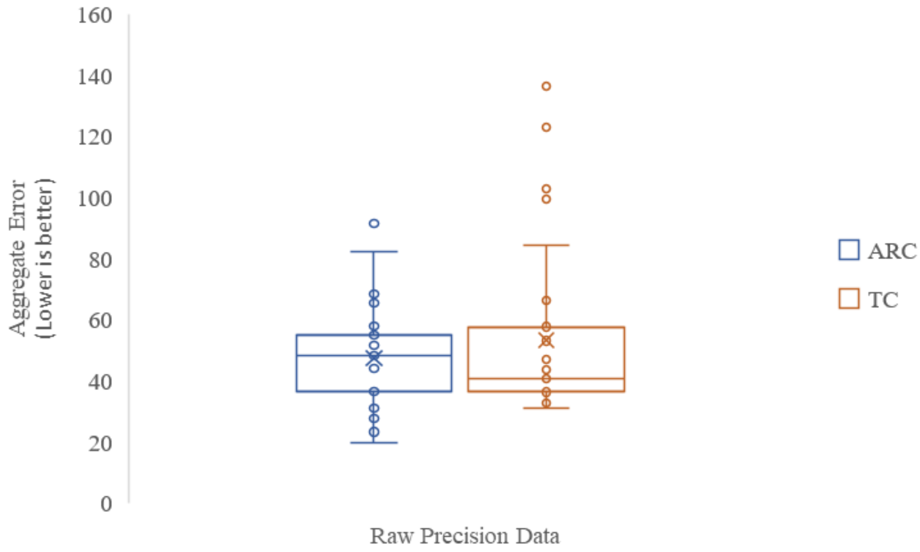

Figure 25. Raw ARC and TC Aggregate Complexity Error (mm). Paired t test (TC minus ARC) results indicate that AR is not statistically different than TC ($\bar{x}_D = 5.81$, $SE_D = 5.02$, $t(30) = 1.16$, $p = 0.2557$, $95\% CI\left[-4.43, 16.06\right]$).

e. Task 5 (Assembly Complexity Error)

One subject failed to complete the task. Figure 26 is a histogram and boxplot, and Figure 27 is a Wilcoxon on each pair of the remaining differential precision data.

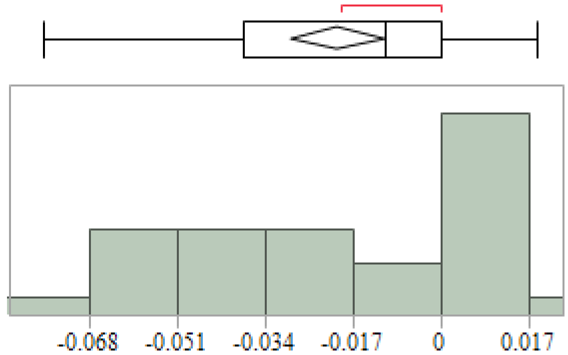

Figure 26. Histogram and Boxplot of ARC Minus TC Aggregate Assembly Complexity Error (mm) ($\bar{x}_D = -0.02003$, $s_D = 0.025$, $SE_D = 0.0044$, $95\%CI[-0.02906, -0.011]$, $n = 32$).

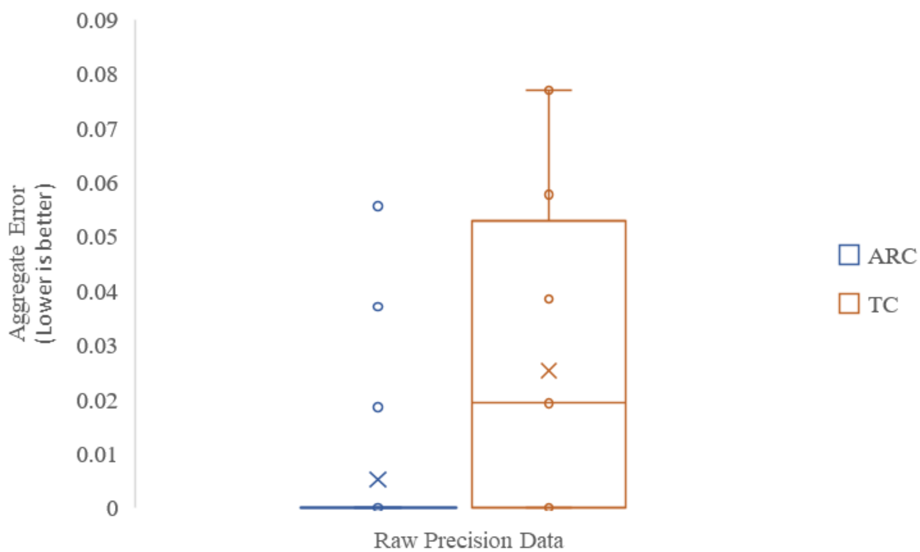

Figure 27. Raw ARC and TC Aggregate Assembly Complexity Error (mm). Wilcoxon on each pair (TC minus ARC) indicate that AR is statistically more precise than TC (score $\bar{x}_D = 25.53$, $SE_D = 4.53$, $z = 5.64$, $p < 0.0001$, $95\%CI[0.01, 0.029]$).

3. Time

This data represents the time in seconds from the beginning of precise motor skill activation to place a part in position to the end of the placement. Extracted data is for each part within task 4 for both conditions. The analysis does not include one subject's corrupted ARC data and associated paired data.

a. Long Part

Two subjects presented outlier data greater than three times interquartile range. This analysis did not include the subjects, but Appendix I contains the original analysis with the subjects' data. Figure 28 is a histogram and boxplot, and Figure 29 is a Wilcoxon on each pair of the remaining differential time data.

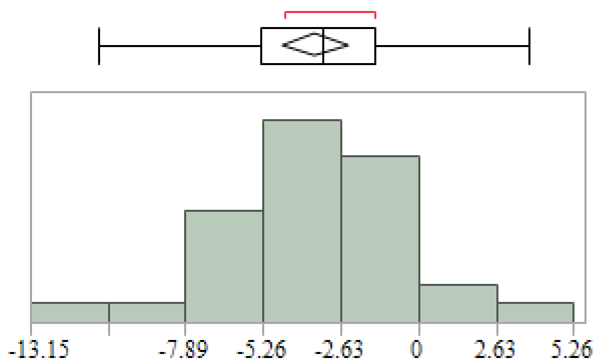

Figure 28. Histogram and Boxplot of ARC Minus TC Time of only Precise Action (seconds) ($\bar{x}_D = -3.506$, $s_D = 3.064$, $SE_D = 0.55$, $95\%CI\left[-4.631, -2.382\right]$, $n = 31$).

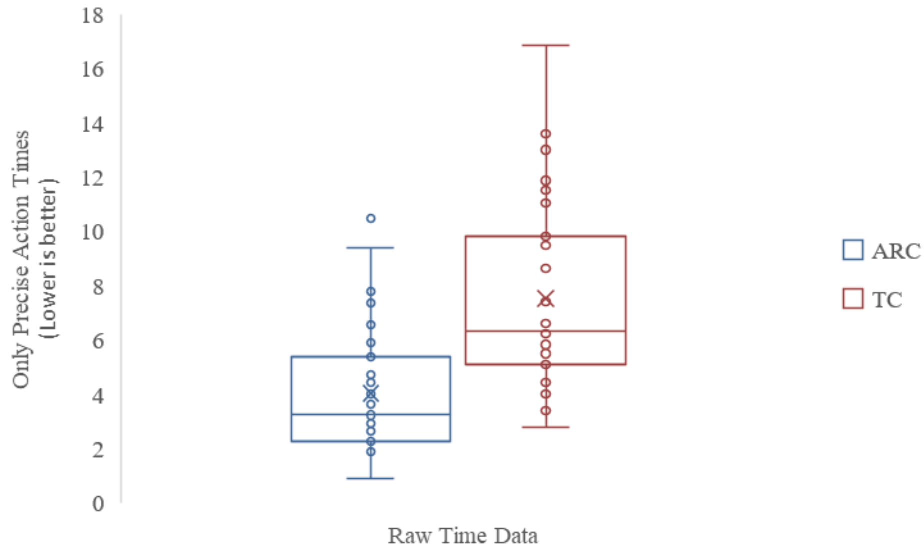

Figure 29. Raw ARC and TC Times for Precise Action (seconds). Wilcoxon on each pair (TC minus ARC) indicate that ARC is statistically faster than TC (score $\bar{x}_D = 28.13$, $SE_D = 4.58$, $z = 6.138$, $p < 0.0001$, $95\% CI\left[2.7167, 4.183\right]$).

b. *Square Part*

Figure 30 is a histogram and boxplot, and Figure 31 is a Wilcoxon on each pair of the remaining differential time data.

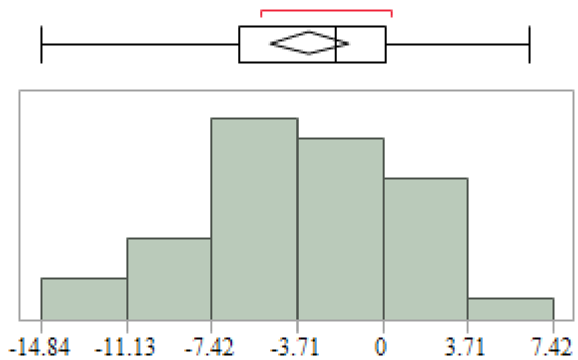

Figure 30. Histogram and Boxplot of ARC Minus TC Time of only Precise Action (seconds) ($\bar{x}_D = -3.157$, $s_D = 4.763$, $SE_D = 0.829$, $95\%CI\left[-4.845, -1.467\right]$, $n = 33$).

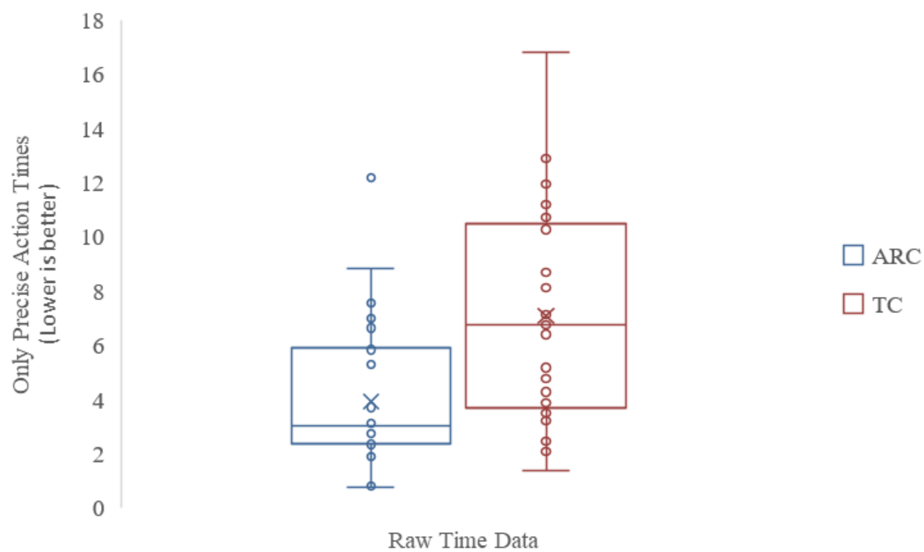

Figure 31. Raw ARC and TC Times for Precise Action (seconds). Wilcoxon on each pair (TC minus ARC) indicate that ARC is statistically faster than TC (score $\bar{x}_D = 21.697$, $SE_D = 4.73$, $z = 4.591$, $p < 0.0001$, $95\%CI\left[1.783, 4.223\right]$).

c. C Part

Two subjects failed to complete the task and one subject presented outlier data greater than three times the interquartile range. This analysis did not include the subjects, but Appendix I contains the original analysis with the subjects' data. Figure 32 is a histogram and boxplot, and Figure 33 is a Wilcoxon on each pair of the remaining differential time data.

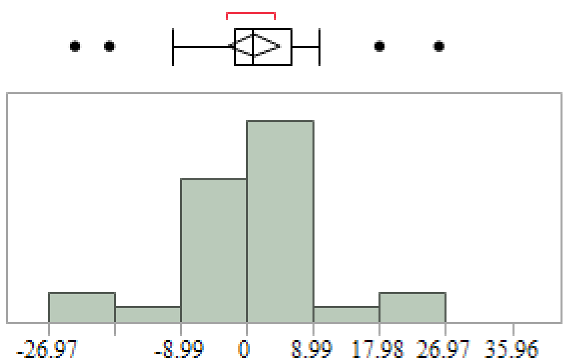

Figure 32. Histogram and Boxplot of ARC Minus TC Time of only Precise Action (seconds) ($\bar{x}_D = 1.0967$, $s_D = 9.187$, $SE_D = 1.677$, $95\% CI\left[2.334, 4.527\right], n = 30$).

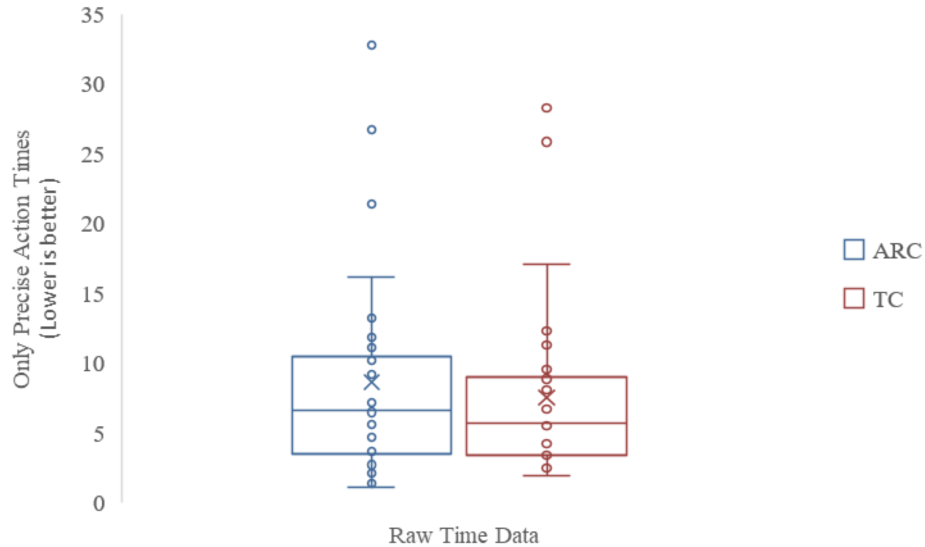

Figure 33. Raw ARC and TC times for Precise Action (seconds). Wilcoxon on each pair (TC minus ARC) indicate that ARC not statistically different than TC (score $\bar{x}_D = -6.3$, $SE_D = 4.509$, $z = -1.397$, $p = 0.1624$, 95% CI [-3.016, 0.45]).

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V. DISCUSSION

A. HUMAN EFFICIENCY

Completion time and precision combine in a simple algorithm to form efficiency data. Table 3 depicts the statistical advantage ARC has over every task within this experiment with respect to efficiency.

Table 3. Efficiency Statistics

	Error Type	95% Confidence Interval		P Value	Condition Advantage
Task 1	Absolute	4313.24	10432.18	<0.0001	ARC
Task 2	Cumulative	3197.59	9930.9	<0.0001	ARC
Task 3	Absolute Referential	3009.2	5507.2	<0.0001	ARC
Task 4	Complexity (Placement – Total Completion Time)	34676.28	40540.03	<0.0001	ARC
Task 4	Complexity (Placement – Placement Only Time)	1072.81	2863.63	<0.0001	ARC
Task 5	Complexity (Assembly)	8.264	166.15	0.0315	ARC

Table 3 summarizes the results from Chapter IV, Section D.1, which shows that, for the reduced maintenance activity spectrum of this research, ARC procedures have a significant efficiency advantage over TC procedures. These findings are in agreement with the research of (Tang et al., 2003) and (Henderson & Feiner, 2011), and directly impacts various DoD and industry applications. A few examples could be: ship construction within drilling, cutting, welding actions which require some measurement to complete, rebuilding small complex objects made of many parts, wire routing during assembly of complex products, or even fixed intermediate level maintenance activity repair work. If object recognition is sufficient enough to properly align the virtual world within the real and identify specific parts, on-site maintenance is viable.

B. HUMAN PRECISION

Various factors affect precision within this experiment. ARC procedures express precision from the AR hardware and software based on virtual world anchoring, tracking, calibration, and stabilization. Individuals' sensory, perceptive, and cognitive abilities (SPC) and precise motor skills operate from that baseline as annotated in Chapter II, Section E.1. TC procedures produce precision via physical measuring implements and their calibration, and the individuals' SPC, and precise motor skills as described in Chapter II, Section E.2. The SPC loads of ARC and TC individual actions might be different.

Table 4 summarizes the precision statistics for every task. Absolute error, cumulative error and complexity error (placement) shows no clear evidence of statistical difference. When only regarding precision, Table 4 shows that absolute error tends towards TC, cumulative error tends strongly towards ARC, and complexity (placement) tends towards ARC as advantageous. Statistically, it is very advantageous to use TC procedures to address absolute referential error and ARC procedures to address complexity error (assembly) when only regarding precision.

Table 4. Precision Statistics

	Error Type	95% Confidence Interval		P Value	Condition Advantage
Task 1	Absolute	-20.22	5.47	0.249	Neither
Task 2	Cumulative	-0.12	34.2	0.0648	Neither
Task 3	Absolute Referential	-23.99	-4.427	0.0058	TC
Task 4	Complexity (Placement)	-4.43	16.06	0.2557	Neither
Task 5	Complexity (Assembly)	0.01	0.029	<0.0001	ARC

As a general statement, ARC procedures are not sufficiently different from TC procedures with respect to precision and small parts. When measuring absolute referential error, ARC was statistically less precise than TC procedures while ARC was statistically more precise than TC procedures during the assembly task.

Hardware, software, and human performance created this precision data. The precision data is not a general statement for all AR devices but specifically for both Microsoft HoloLens and the population of Marines that volunteered for this research. Additionally, the calibration routine did not appear optimized for close in work. As the technology progresses, precision will improve.

C. INTERESTING FINDING

Task 4, which directs the subject to place three parts within their workspace, has exposed a more fundamental difference than surface efficiency or precision comparisons. For the TC condition of the experiment, subjects completed a wire diagram first and then placed physical parts upon the diagram. This separated the measuring and drawing from the part placement action within the TC condition for this task. The ARC condition has no measuring or drawing component and prompts the subject to place parts directly. Both conditions' placement only efficiency data, depicted in Figure 15, shows ARC is statistically more efficient while Figure 25, representing only precision, is not statistically different. These results precipitated another level of analysis captured within Chapter IV, Section D.3 which focused only on timing. All timing began from the transition to precise motor movements. With this more focuses look, ARC procedures are still statistically faster than TC for two out of the three parts. This necessitates a more granular determination of why the time to place a part guided by AR is statistically faster than placing a part upon a line an individual has already created. The SPC requirements between the two may be different for a similar task. For example, understanding where correct object placement guided by AR is different than a technical manual. AR may use a hologram of a wire mesh the size of the part vice text, numbers and pictures for the technical manual. This finding could be the result of different guidance structures presented by each medium. A much more granular experiment focused on this theory and analysis of the SPC requirements of each guidance structure may explain the difference. The author believes that the guidance structure of ARC placement tasks contains less magnitude and number of SPC requirements than the same motion outside of AR with a different guidance structure (lines).

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VI. CONCLUSION

A. IMPLICATIONS

As industry advances the capability of AR platforms, the DoD must understand how AR technology can be leveraged to best advantage. This research scoped the spectrum of all maintenance activity to small part placement, an assembly task consisting of small parts, and wire routing.

This thesis addressed the problem of efficiency and precision in maintenance tasks using ARC procedures hypothesizing that there is a statistical difference in both efficiency and precision when comparing AR to a technical manual. An experiment with 34 Marine maintenance professionals showed that ARC procedures are statistically more efficient for human precise placement tasks of small parts, while precision is roughly equal. The assembly task, analogous to an assembly procedure, is statistically both more efficient and more precise using ARC vice TC procedures. In conclusion, ARC procedures for small part placement and assembly tasks, including wiring, are more efficient, faster, and in most cases at least as precise.

B. FUTURE WORK

Given the wide breadth of procedural work and the potential impact small clarifying adjustments can have on the maintenance domain as a whole, it is essential to extend and expand research in this area. The following avenues are critical extensions:

- Enlarge the size of the parts. Is there a definable curve or correlation to size of parts and human precision and efficiency?

- Expand the sample types. How do other military services perform? Shipyard, automobile, and factory assembly professionals, are there differences? Does this research hold true outside of pure maintenance professionals?

- Ambiguity of task. Is there a definable transition where intuitiveness, simplicity, or repetitiveness of a task overrides the benefits of ARC?

- Quality Assurance. To what extent does AR impact the correctness of maintenance actions?
- Performance Metrics. What metrics are available to AR that is not available in other domains? Can these metrics better inform job performance? Can these metrics inform proficiency and proficiency decay?
- Training. What impact does AR have on accession training? Is it possible some knowledge, skills and attitudes are less important when using AR?
- Logistics. To what extent does AR enable more precise maintenance actions? Can AR's objectivity help maintenance focus only on required repairs, not repairs based on time?
- Calibration and Localization. What effect do these factors have on various ARC tasks? Is there a definable correlation between calibration and off-axis work?

The author intends to investigate the unexplained advantage that ARC holds over TC with respect to placement of small parts when evaluating only precise motor movements.

C. FINAL THOUGHTS

ARC procedures, for small parts, require less steps to complete than technical manuals based on multiple factors. While procedures with less steps are generally faster, AR presents information in a more palatable form. This form appears to require a reduced number and magnitude of individual knowledge, skills and abilities for a similar precise action from a TC procedure. Is this the advantage AR has over traditional methods of communication? Specifically, the manner in which AR applications present information may be the fundamental and most meaningful advantage AR has over TC procedures.

APPENDIX A. TECHNICAL MANUAL

A representative technical manual follows. The thesis author conceptualized, designed, and built this manual, including the procedures themselves. For formatting considerations, the manual begins on the following page.

A0001-AA-STM-001

REVISION 0

ANGELOPOULOS SYSTEM TECHNICAL MANUAL
CHAPTER 001

VOLUME 1 – PROCEDURES FOR EXPERIMENTAL STUDY OF HUMAN EFFICIENCY AND PRECISON OF MAINTENANCE TASKS

SUPERSEDURE NOTICE: THIS MANUAL SUPERSEDES ALL PRIOR VOLUMES[1]
AND ALL CHANGES THERETO.

[1] Crest image Source: Department of the Navy (2011, August 1). *NSTM 074 Gas Free Engineering Vol 3 Rev 6*. Washington, DC. retrieved from http://public.navy.mil

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REVISION 0

INTRODUCTION

This portion of the experiment with guide you through 5 sections of traditionally cued procedures. You will perform basic measuring, placement, and building actions. Data from this experiment informs future acquisition decisions relating to your field of expertise.

BACKGROUND

The experiment is focusing on your individual ability to measure with BOTH precision and speed. A ruler and a protractor afford the ability to place small objects.

TRAINING SECTION

The first section will refresh your memory for the use of a ruler and a protractor.

The maximum time for this section is **30 minutes**.

You may ask questions or repeat work.

This is your time to become comfortable with the tools.

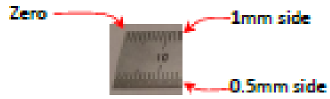
If you have not used a protractor, spend the majority of the time doing that work.

You do not need to complete all of the work.

When you are ready to begin:

1) Say "Begin"
2) Turn the page

RULER Exercise:



Facts: The square edge is zero, the smallest marks are 0.5mm, the other side's minimum is 1mm

STEP 1: Using group of shapes (first 2) and the ruler

STEP 1a: Measure 5mm to the right of each vertical line, mark with a 'V'.

STEP 1b: Measure 8mm above each horizontal line, mark with an 'H'.

PROTRACTOR Exercise:

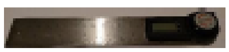
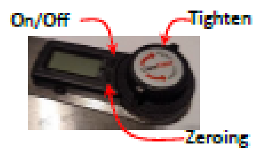


Figure 1



Facts:

- The intersection of the two inner edges must be placed on the vertex of the measured angle
- Greater than 180 degrees can be made by using the other side of the protractor

STEP 2: Using the group of shapes and the protractor

STEP 2a: Measure clockwise from the vertical line. **Write down what angle is formed *under the shape*.**

Do this by turning on the protractor using the on/off button. Line up the straight edges like figure 1. Push the zero button. Open the protractor clockwise (the direction is for the top straightedge) to roughly the correct angle. Line up the inner edge of the bottom straightedge with the vertical line (bear in mind the inner edge is the side of the protractor that forms the smaller angle). Place the vertex of the protractor on the dot of the line. Align the inner edge of the top straightedge on the other line. Read the number.

STEP 3: Using the group of shapes, measure with the protractor, indicated direction and number of degrees. Make a new line from the center dot outward on the measured angle.

****WHEN YOU FEEL CONFIDENT TO BE ABLE TO PERFORM THESE MEASURING ACTIONS:

1) SAY "COMPLETE"

2) TURN THE PAGE

SECTION 1

Your role for this section is to:

1) Place physical objects based on precise measurements you make.

2) Proceed as fast as possible, but ensure you are still placing the physical objects precisely where you measure.

3) You can mark the worksheet as needed.

When you are ready:

1) Say "Begin"

2) Turn the page

Placement of 5 erector set pieces

a) Positioned to the right of your workspace are 5 erector set pieces. Each piece has 4 holes in them. Use the ruler for the measurements.
b) One erector set piece will be placed into each 'L' shape

CAUTION

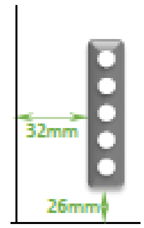
Do not impact the other erector set pieces with your ruler when measuring.

NOTE

SPEED AND PRECISION are evaluated.

Step 1: Take an erector set piece placing it near the leftmost 'L' shape.

Step 2: Orient the erector set piece so the longer edge is vertical



Step 3: Measure 32mm to the right from the vertical line of the 'L' shape.

Step 4: Move the left edge of the erector set piece to line up with the measured distance away from and parallel with the vertical line of the 'L' shape.

Step 5: Measure 26mm up from the horizontal line of the 'L' shape.

Step 6: Move the BOTTOM CENTER EDGE of the erector set piece to line up with the measured distance away from and parallel with the horizontal line of the 'L' shape.

REPEAT THIS PROCESS TO FILL ALL THE 'L' SHAPES WITH THE OTHER ERECTOR SET PIECES

""""WHEN YOU ARE COMPLETE:

1) Say "Complete"

2) Turn the page

SECTION 2

Your role for this section is to:

1) Place physical objects based on precise measurements you make.

2) Proceed as fast as possible, but ensure you are still placing the physical objects precisely where you measure.

When you are ready:

1) Say "Begin"

2) Turn the page

Placement of 5 erector set pieces

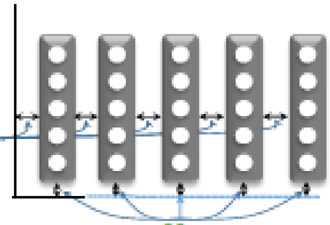
a) Positioned to the right of your workspace are 5 erector set pieces. Each piece has 4 holes in them. Use the ruler for the measurements.
b) All 5 erector set pieces will be placed in a row starting at the 'L' shape

CAUTION

Do not impact the other erector set pieces with your ruler when measuring.

NOTE

SPEED AND PRECISION are evaluated.



Step 1: Take an erector set piece placing it near the 'L' shape.

Step 1a: Orient the erector set piece so the longer edge is vertical

Step 1b: Measure 32mm to the right from the vertical line of the 'L' shape.

Step 1c: Move the left edge of the erector set piece to line up with the measured distance away from and parallel with the vertical line of the 'L' shape.

Step 1d: Measure 26mm above the horizontal line of the 'L' shape.

Step 1e: Move the BOTTOM CENTER EDGE of the erector set piece to line up with the measure distance away from and parallel with the horizontal line of the 'L' shape.

Step 2: Take an erector set piece placing it to the right of the last erector set piece

Step 2a: Orient the erector set piece so the longer edge is vertical

Step 2b: Measure 32mm from the right edge of the last erector part to the left edge of the new erector set piece.

Step 2c: Move the left edge of the erector set piece to line up with the measured distance away from and parallel with the last erector set part.

Step 2d: Move the BOTTOM EDGE of the erector set piece to line up with the previous erector set piece.

NOTE

All pieces should be vertically parallel and horizontally in a line

***REPEAT STEP 2-2d FOR ALL REMAINING ERECTOR SET PARTS

****WHEN YOU ARE COMPLETE:

1) Say "Complete"

2) Turn the page

SECTION 3

Your role for this section is to:

1) Place physical objects based on precise measurements you make.

2) Proceed as fast as possible, but ensure you are still placing the physical objects precisely where you measure.

When you are ready:

1) Say "Begin"

2) Turn the page

Placement of 5 erector set pieces

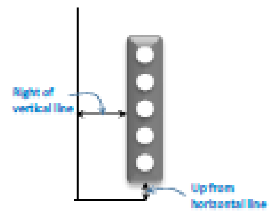
a) Positioned to the right of your workspace are 5 erector set pieces. Each piece has 4 holes in them. Use the ruler for the measurements.
b) One erector set piece will be placed into each 'L' shape

CAUTION

Do not impact the other erector set pieces with your ruler when measuring.

NOTE

SPEED AND PRECISION are evaluated.



Step 1: Take an erector set piece placing it near the leftmost 'L' shape.

Step 1a: Place the left edge of the erector set piece 22mm right of the vertical line of the 'L' shape, and the BOTTOM CENTER EDGE 23mm above the horizontal line of the 'L' shape.

Step 2: Take another erector set piece placing it near the next 'L' shape to the right.

Step 2a: Place the left edge of the erector set piece 21mm right of the vertical line of the 'L' shape, and the BOTTOM CENTER EDGE 37mm above the horizontal line of the 'L' shape.

Step 3: Take another erector set piece placing it near the next 'L' shape to the right.

Step 3a: Place the left edge of the erector set piece 26mm right of the vertical line of the 'L' shape, and the BOTTOM CENTER EDGE 21mm above the horizontal line of the 'L' shape.

Step 4: Take another erector set piece placing it near the next 'L' shape to the right.

Step 4a: Place the left edge of the erector set piece 33mm right of the vertical line of the 'L' shape, and the BOTTOM CENTER EDGE 27mm above the horizontal line of the 'L' shape.

Step 5: Take another erector set piece placing it near the next 'L' shape to the right.

Step 5a: Place the left edge of the erector set piece 28mm right of the vertical line of the 'L' shape, and the BOTTOM CENTER EDGE 32mm above the horizontal line of the 'L' shape.

****WHEN YOU ARE COMPLETE:

1) Say "Complete"

2) Turn the page

SECTION 4

Your role for this section is to:

1) Place physical objects based on precise measurements you make.

2) Proceed as fast as possible, but ensure you are still placing the physical objects precisely where you measure.

When you are ready:

1) Say "Begin"

2) Turn the page

Placement of 3 erector set pieces

a) Positioned to the right of your workspace are 3 erector set pieces.
b) You will place the erector set pieces to form a specific pattern. Use the ruler and protractor for measurements.
c) **Marking the sheet is for your benefit.** These lines are not evaluated.

CAUTION	NOTE	NOTE
Do not impact the other erector set pieces when measuring.	You may extend any line as needed to effectively use protractor	**SPEED AND PRECISION** are evaluated.

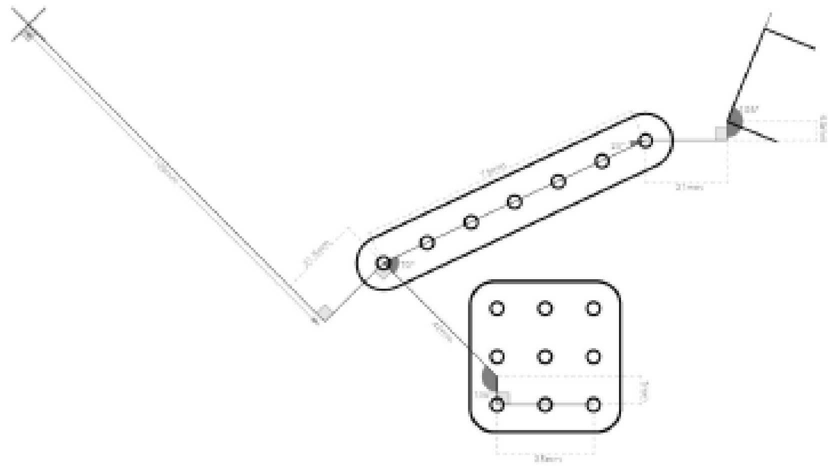


Figure 1: Overview of Part Placement. Source: (R. Lee, personal communication, February 26, 2018)

Step 1: On the sheet, at the middle left side is an 'X'. From the CENTER of the 'X', projecting inline along the 'X' per **figure 2 below**, (top left to bottom right), draw a line 109mm long.

Step 1a: Mark the end of the line 'A'.

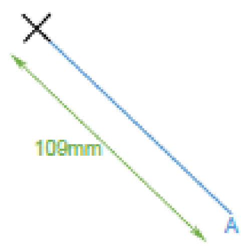


Figure 2: Step 1 & 1a

Step 2: Using 'A' as the vertex of the angle and the line described by the large 'X' and the 'A', measure 90 degrees *clockwise*, per **figure 3 below**, and draw a line 21.5mm long.

Step 2a: Mark the end of the line 'B'.

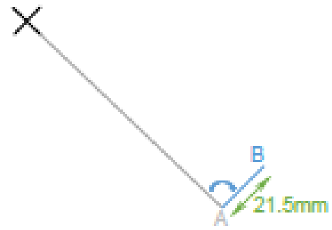


Figure 3: Step 2 & 2a

Step 3: Using 'B' as the vertex of the angle and the line described by 'A' and 'B', measure 90 degrees *counter-clockwise*, per **figure 4 below**, and draw a line 42mm long. Mark the end of the line 'C'.

Step 3a: Label the line BC.

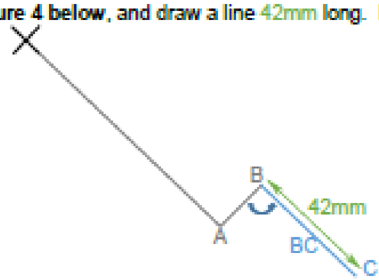


Figure 4: Step 3 & 3a

Step 4: Using 'C' as the vertex of the angle and the line labeled BC, measure 135 degrees *counter-clockwise*, per **figure 5 below**, and draw a line 7mm long.

Step 4a: Mark then end of the line 'D'.

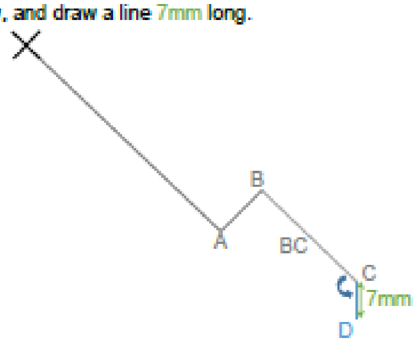


Figure 5: Step 4 & 4a

Step 5: Using 'D' as the vertex of the angle and the line described by 'C' and 'D', measure 90 *clockwise*, per **figure 6 below**, and draw a line 25mm long.

Step 5a: Mark the end of the line 'E'.

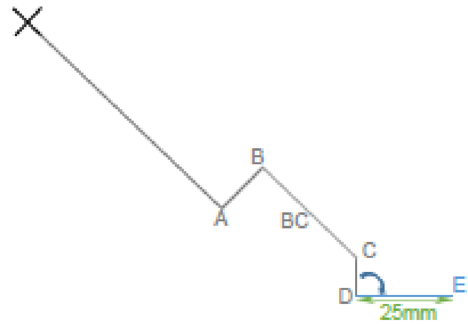


Figure 6: Step 5 & 5a

Step 6: Using 'B' as the vertex of the angle, and the line labeled as BC, measure 70 degrees *counter-clockwise*, per **figure 7 below**. Draw a line 75mm long. Mark the end of the line 'F'.

Step 6a: Label the line BF.

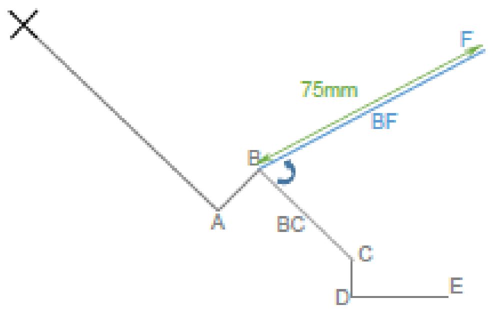


Figure 7: Step 6 & 6a

Step 7: Using 'F' as the vertex of the angle, and the line labeled BF, measure 155 degrees *counter-clockwise*, per figure 8 below. Draw a line 21mm long. Mark the end of the line 'G'.

Step 7a: Label the line FG.

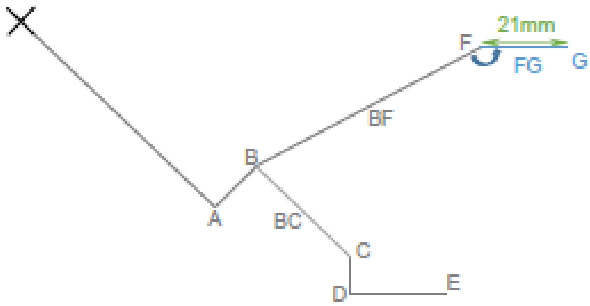


Figure 8: Step 7 & 7a

Step 8: Using 'G' as the vertex of the angle, and the line labeled FG, measure 90 degrees *clockwise*, per figure 9 below. Draw a line 4.5mm long. Mark the end of the line 'H'.

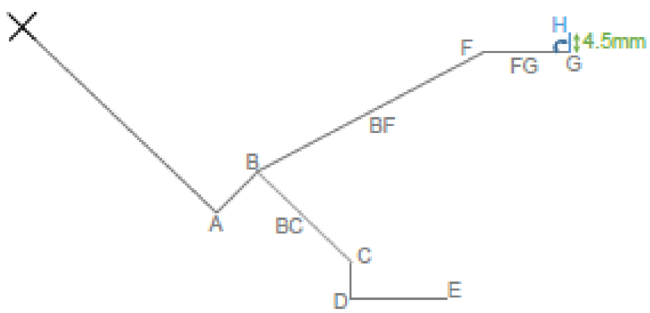


Figure 9: Step 8

Step 9: Using 'H' as the vertex of the angle, and the line described by G and H, measure 158 degrees *counter-clockwise*, per **figure 10 below**. Draw a line 22mm long. Mark the end of the line 'I'.

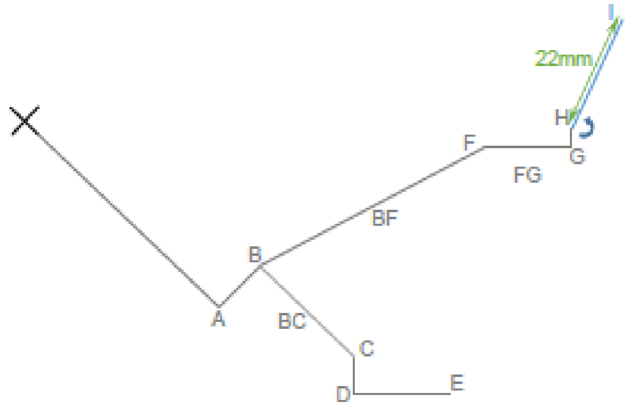


Figure 10: Step 9

Step 9a: Say the word 'FRAMED'

Step 10: Place the longest part, with its' end holes CENTERED over points 'B' and 'F', per **figure 11 below**.

Step 11: Place the square part, with end holes CENTERED over points 'D' and 'E', per **figure 11 below**.

Step 12: Place the double bent part, on its' side, with each 90 degree bend over points 'H' and 'I', **per figure 11 below**.

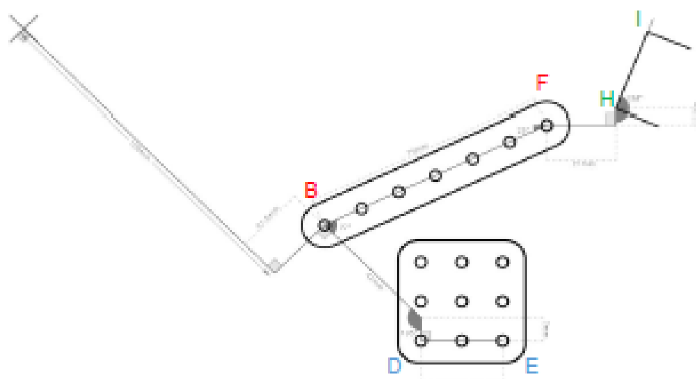


Figure 11: Final Diagram. Adapted from: (R. Lee, personal communication, February 26, 2018)

****WHEN YOU ARE COMPLETE:

1) Say "Complete"

2) Turn the page

SECTION 5

Your role for this section is to:

1) Construct a physical object comprised of erector set parts.

2) Proceed as fast as possible, but ensure you are still connecting the physical objects precisely as indicated.

When you are ready:

1) Say "Begin"

2) Turn the page

Step 1: Gather 4 parts: large rectangular box, one long straight part, one long bolt, one thick black plastic washer.

Step 1a: Feed the long bolt through the washer, through the last hole in the long part and through hole 5 of the large rectangular box from the right, as depicted on **figure 12 below**.

Step 1b: Hold parts in place and turn the page.

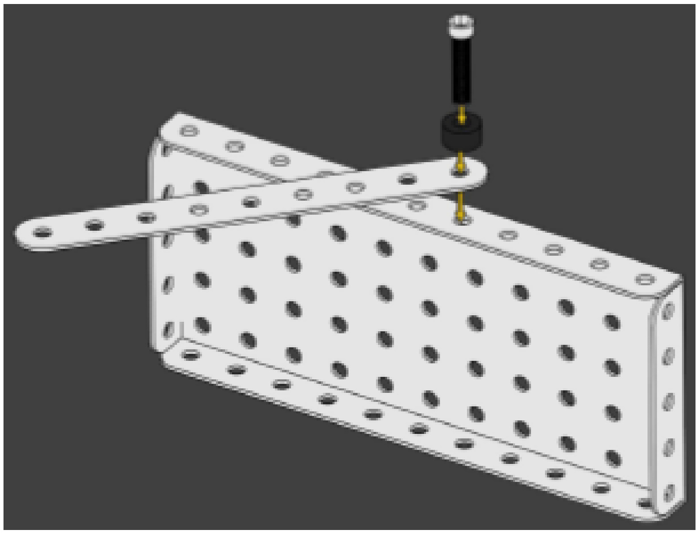


Figure 12: Step 1 & 1a. Source: (R. Lee, personal communication, February 26, 2018)

Step 2: Gather 4 parts: one long part, 2 thin silver washers and 1 silver nut.

Step 2a: Per **figure 13 below**, place the 2 thin silver washers, then the long part and the nut (in that order) on the long bolt from last step. Tighten bolt while stabilizing nut (just enough to be snug).

Step 2b: Turn the page.

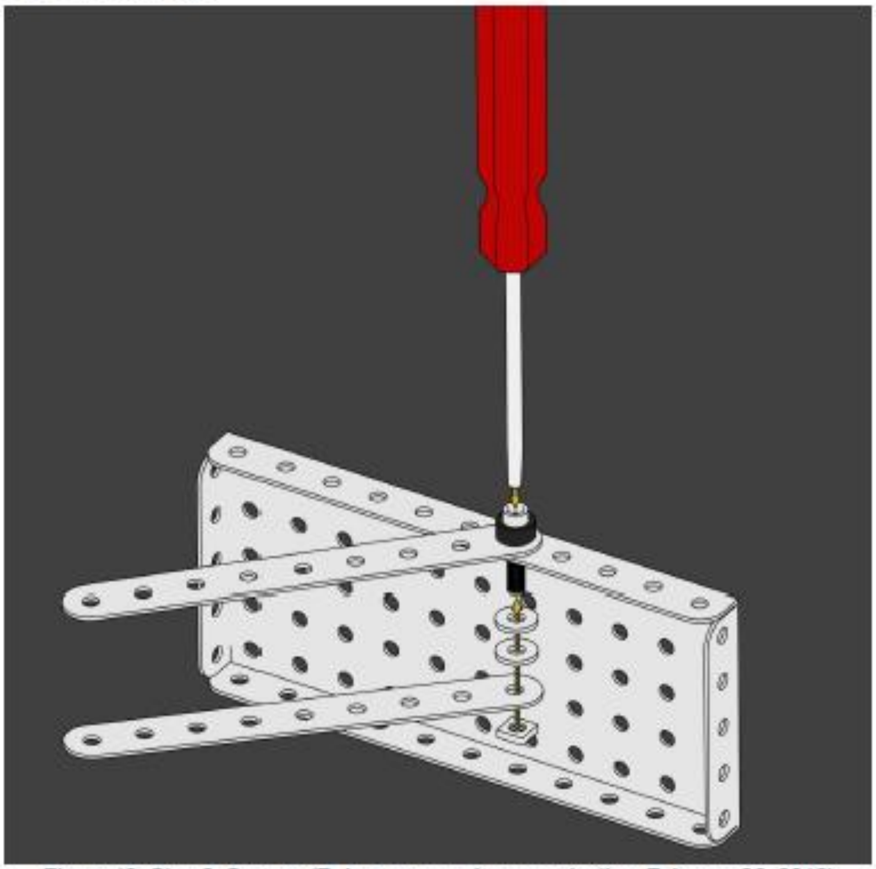


Figure 13: Step 2. Source: (R. Lee, personal communication, February 26, 2018)

Step 3: Gather 2 parts: 1 short bolt, 1 nut

Step 3a: Per **figure 14 below**, place the bolt through both of the end holes of the long parts. The bolt will be entering the same direction as the long bolt. (notice the figure has rotated 180 degrees). Place the nut on the other side. Tighten bolt (just snug).

Step 3b: Turn the page.

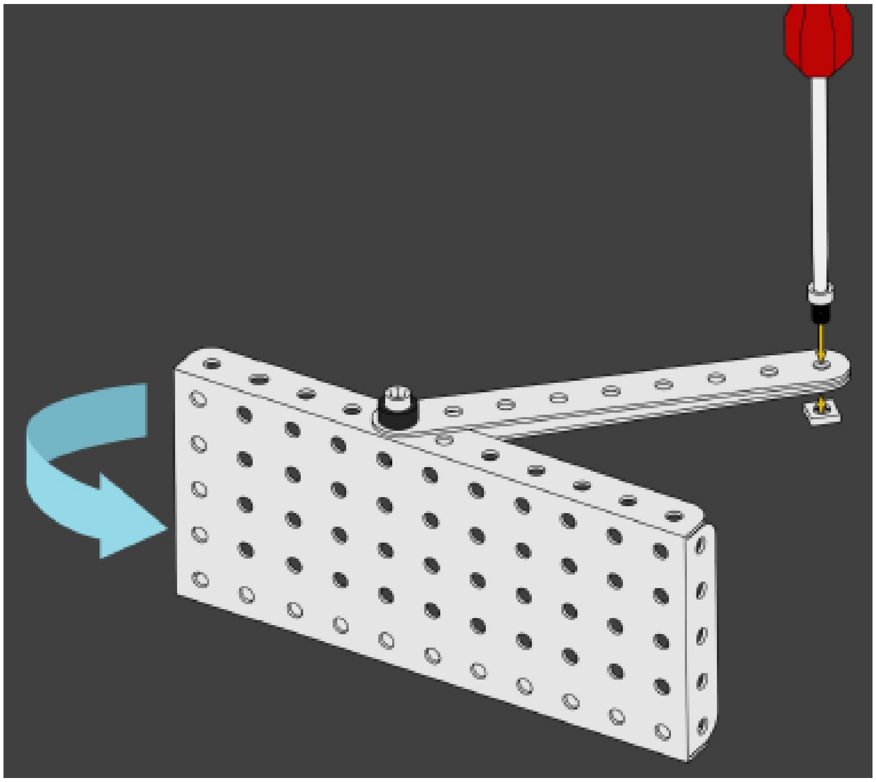


Figure 14: Step 3. Source: (R. Lee, personal communication, February 26, 2018)

Step 4: Gather 2 parts: 1 short bolt, 1 nut

Step 4a: Per **figure 15 below**, insert the bolt the OPPOSITE direction of the other bolts, and secure it with a nut. Tighten bolt (just snug)

Step 4b: Turn the page.

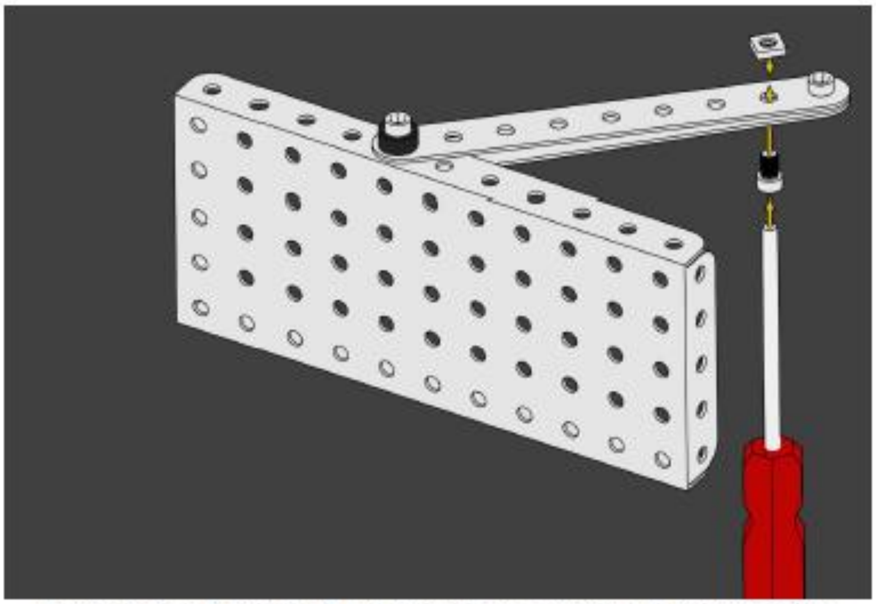


Figure 15: Step 4. Source: (R. Lee, personal communication, February 26, 2018)

Step 5: Gather 3 parts: Double bent part, 1 short bolt, 1 nut.

Step 5a: Per figure 16 below, find the hole (one up, one in) from the corner opposite side of the other attached parts.

Step 5b: Insert bolt through center hole of double bent part, the appropriate hole in large rectangular part, and secure the other side of the bolt with a nut. Tighten bolt (just snug).

Step 5c: Turn the page.

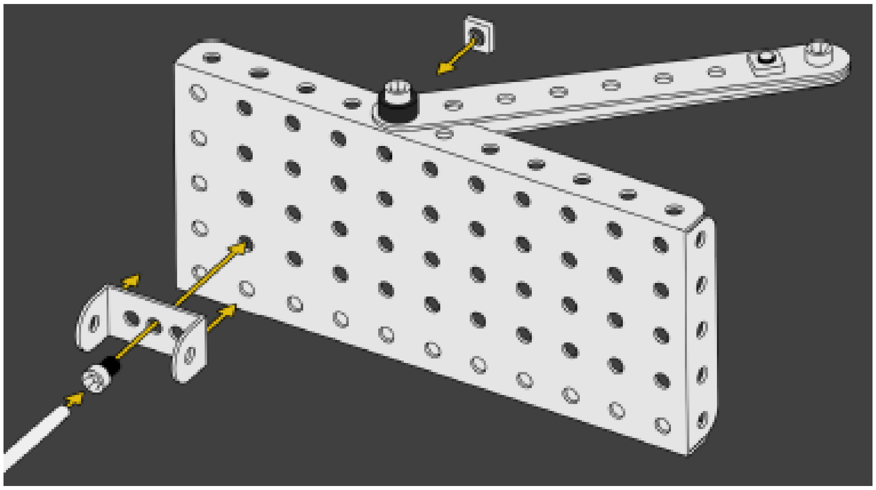


Figure 16: Step 5 - 5b. Source: (R. Lee, personal communication, February 26, 2018)

Step 6: Gather wire

Step 6a: Feed entire wire through holes indicated in **figure 17 below**, with only 10mm left over.

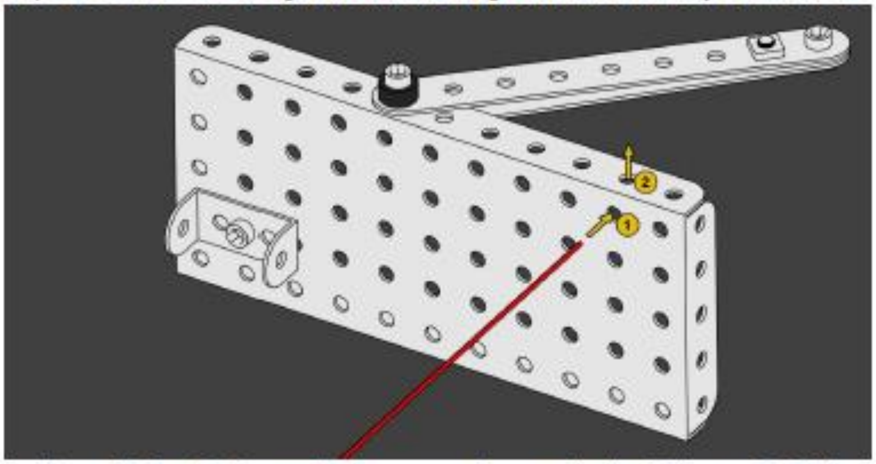


Figure 17: Step 6a. Source: (R. Lee, personal communication, February 26, 2018)

Step 7: Thread the wire downward through hole 1 depicted on **figure 18 below**. Bring the wire towards you and upwards until slack is taken out.

Step 7a: Thread the wire downward again through hole 2 depicted on **figure 18 below**. It will wrap around the long part.

Step 7b: Turn the page.

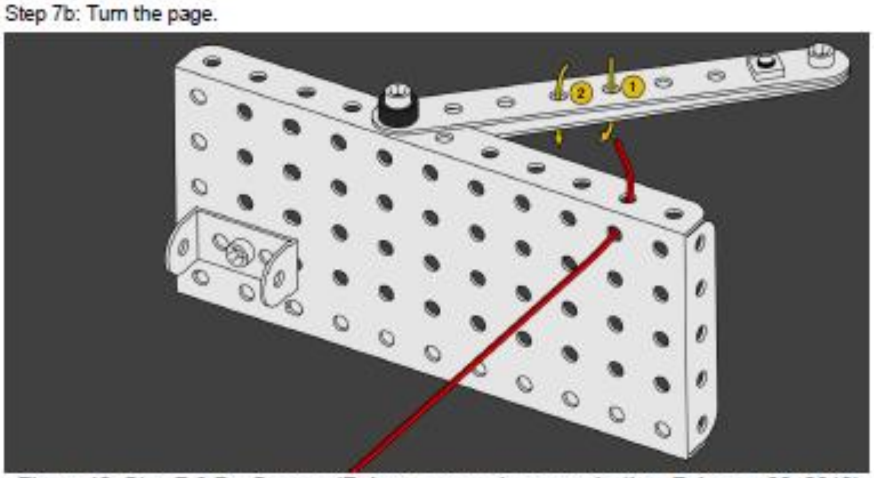


Figure 18: Step 7 & 7a. Source: (R. Lee, personal communication, February 26, 2018)

Step 8: Gather end toward you and feed the wire downward through hole 1 per **figure 19 below**.

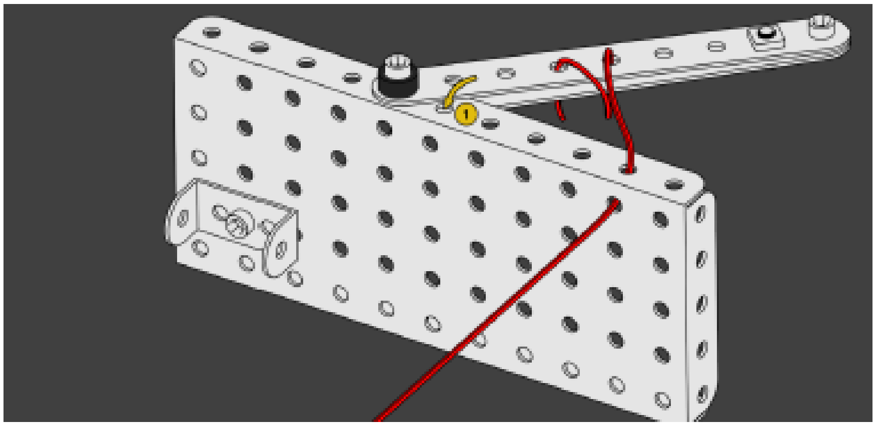


Figure 19: Step 8. Source: (R. Lee, personal communication, February 26, 2018)

Step 9: Pull the wire towards you, over the long part and downward into the hole per **figure 20 below**.

Step 9a: Turn the page.

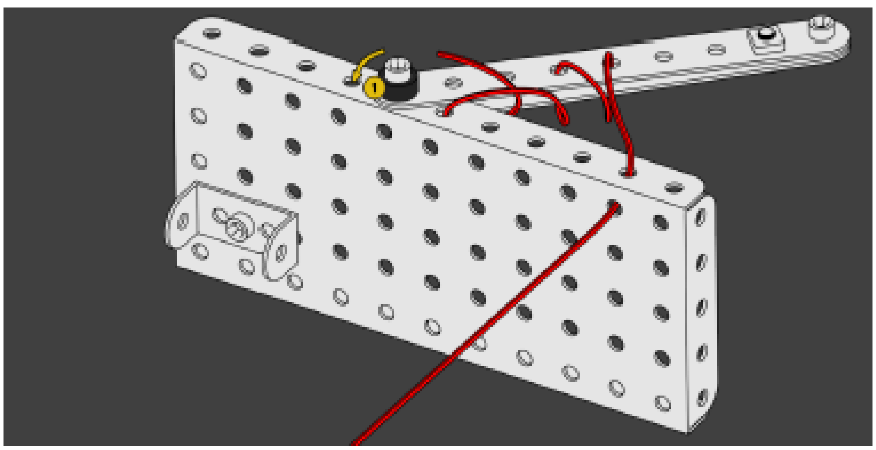


Figure 20: Step 9. Source: (R. Lee, personal communication, February 26, 2018)

Step 10: Pull the wire towards you and then outward through hole one, then up through hole 2 per **figure 21 below**.

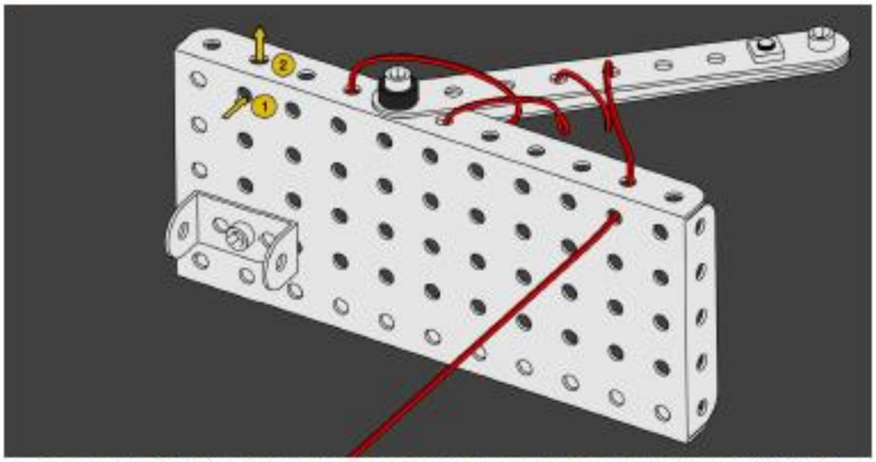


Figure 21: Step 10. Source: (R. Lee, personal communication, February 26, 2018)

Step 11: Pull the wire upward, then feed the wire downward through hole 1 indicated **per figure 22**.

Step 11a: Turn the page.

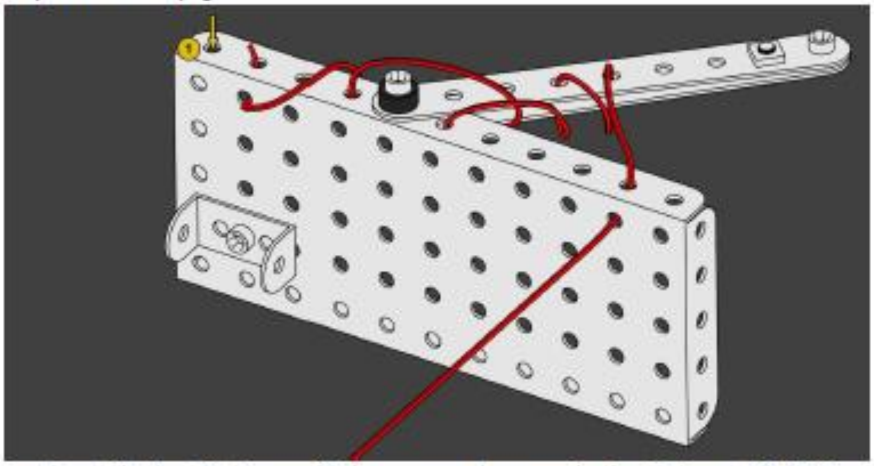


Figure 22: Step 11. Source: (R. Lee, personal communication, February 26, 2018)

Final product: This is what your object should look like

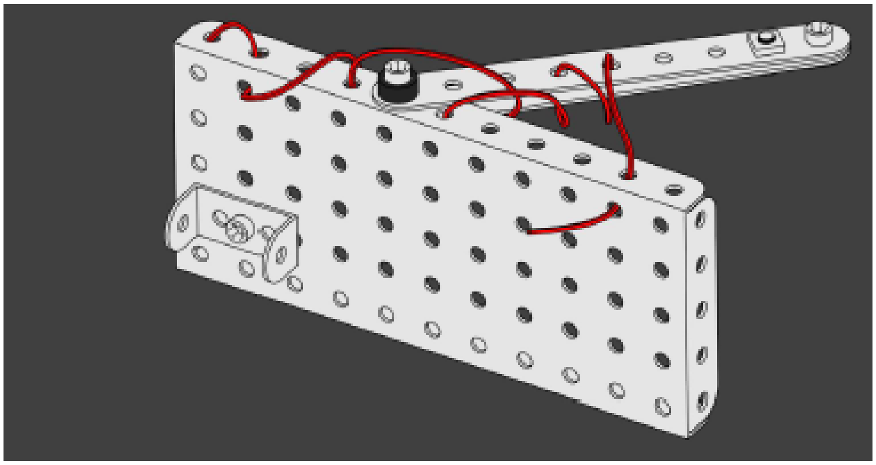


Figure23: Final Outcome. Source: (R. Lee, personal communication, February 26, 2018)

****WHEN YOU ARE COMPLETE:

1) Say "Complete"

APPENDIX B. WORKSPACE SHEETS

These figures represent the workspaces per task. To use them in the real world one must print them on 11x17 paper and ensure proper scaling. The thesis author conceptualized and designed these sheets.

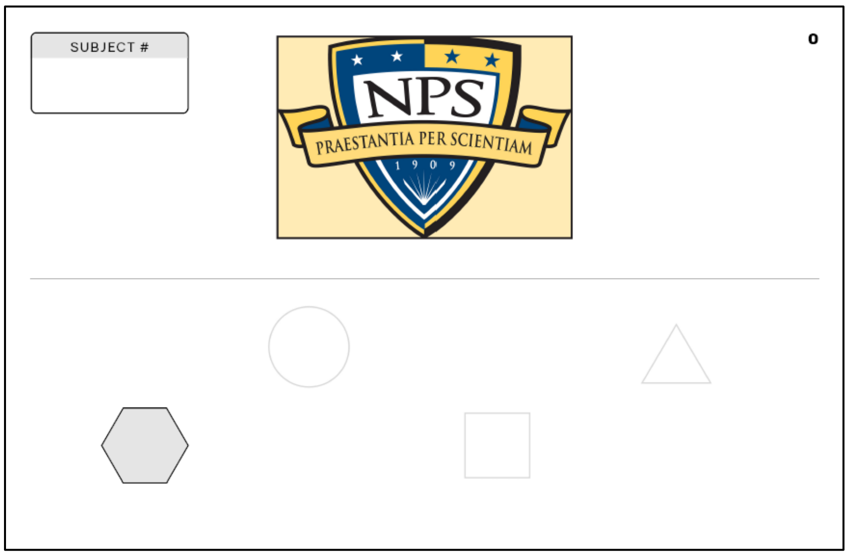


Figure 34. Workspace for ARC Training Task. Source: (R. Lee, personal communication, March 23, 2018)

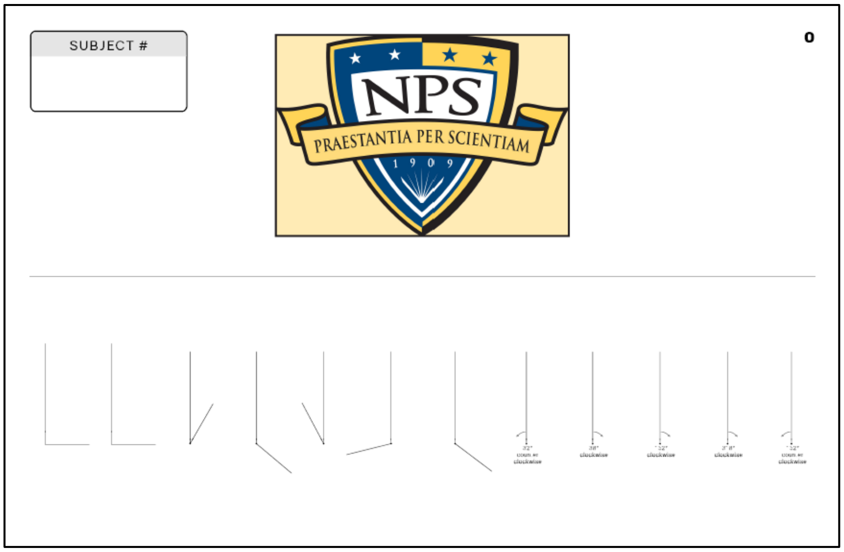


Figure 35. Workspace for TC Training Task. Source: (R. Lee, personal communication, March 23, 2018)

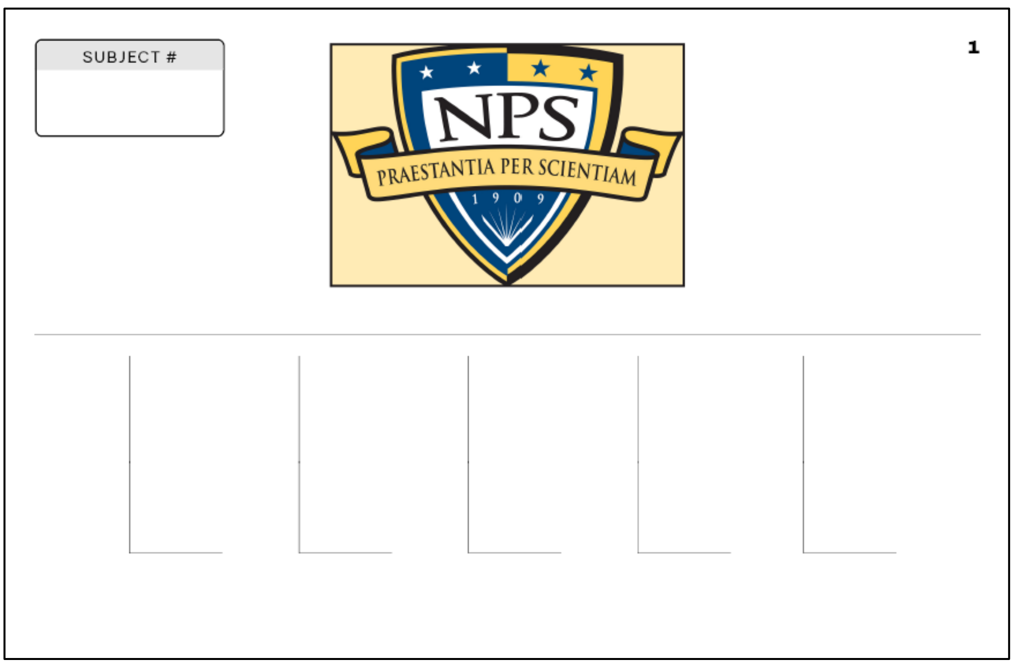


Figure 36. Workspace for Task 1. Source: (R. Lee, personal communication, March 23, 2018)

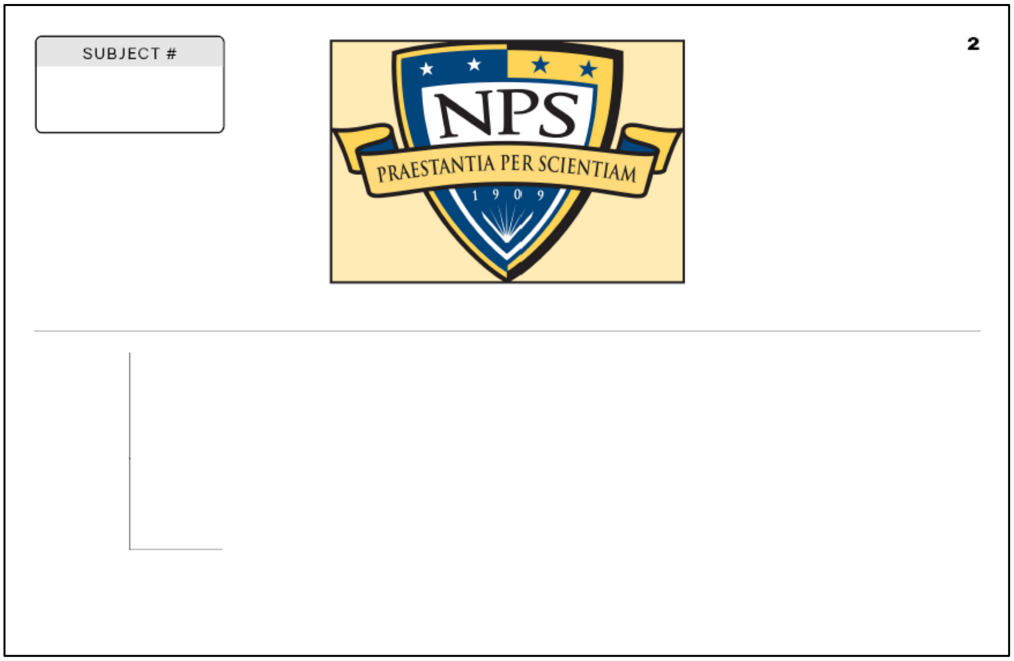


Figure 37. Workspace for Task 2. Source: (R. Lee, personal communication, March 23, 2018)

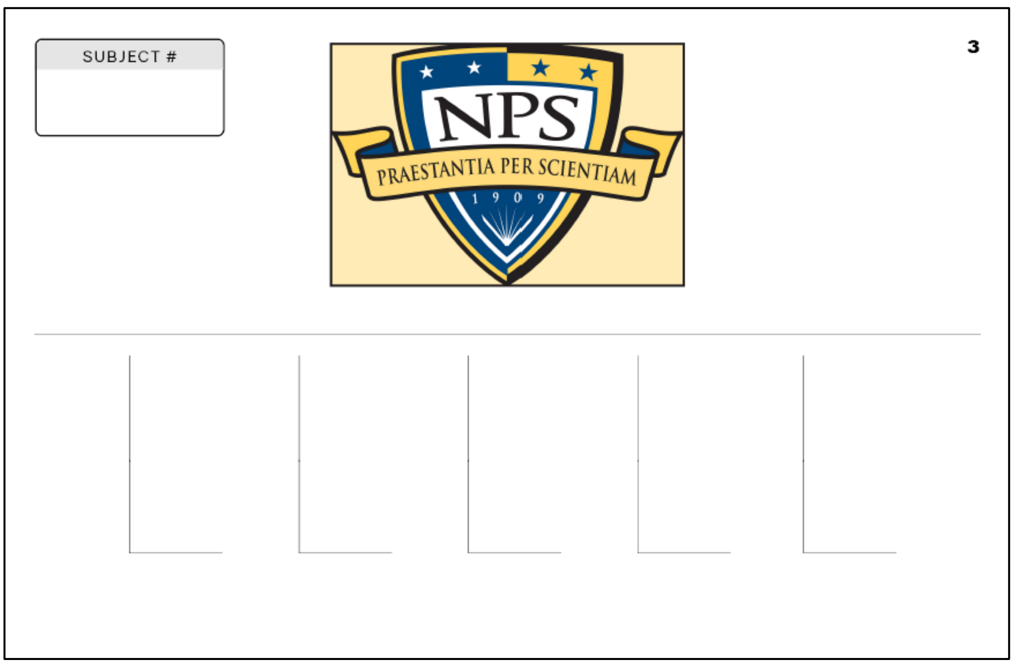


Figure 38. Workspace for Task 3. Source: (R. Lee, personal communication, March 23, 2018)

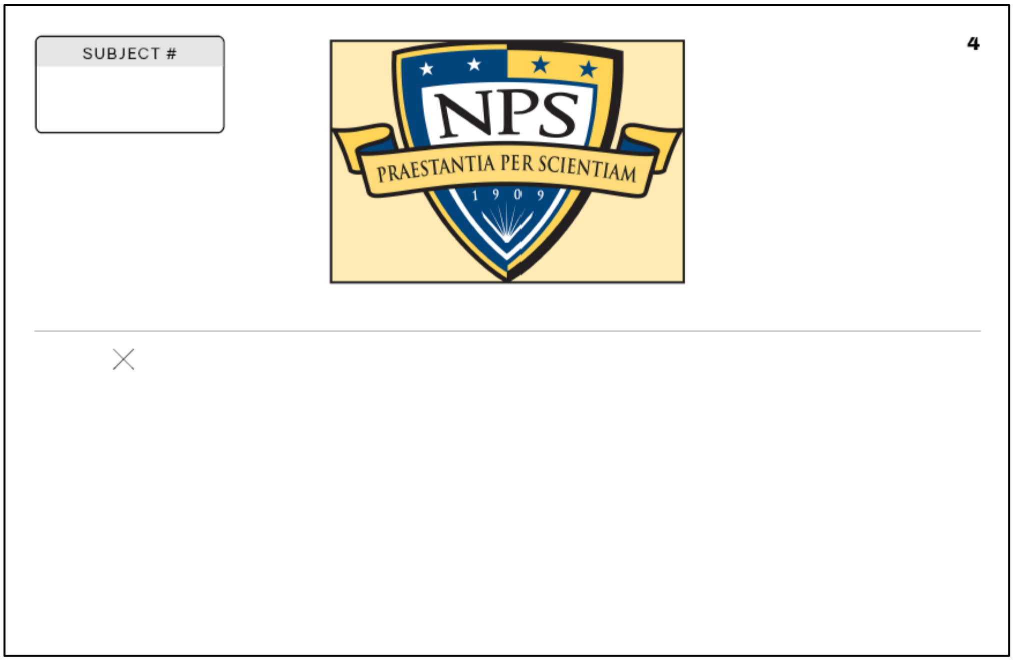


Figure 39. Workspace for Task 4. Source: (R. Lee, personal communication, March 23, 2018)

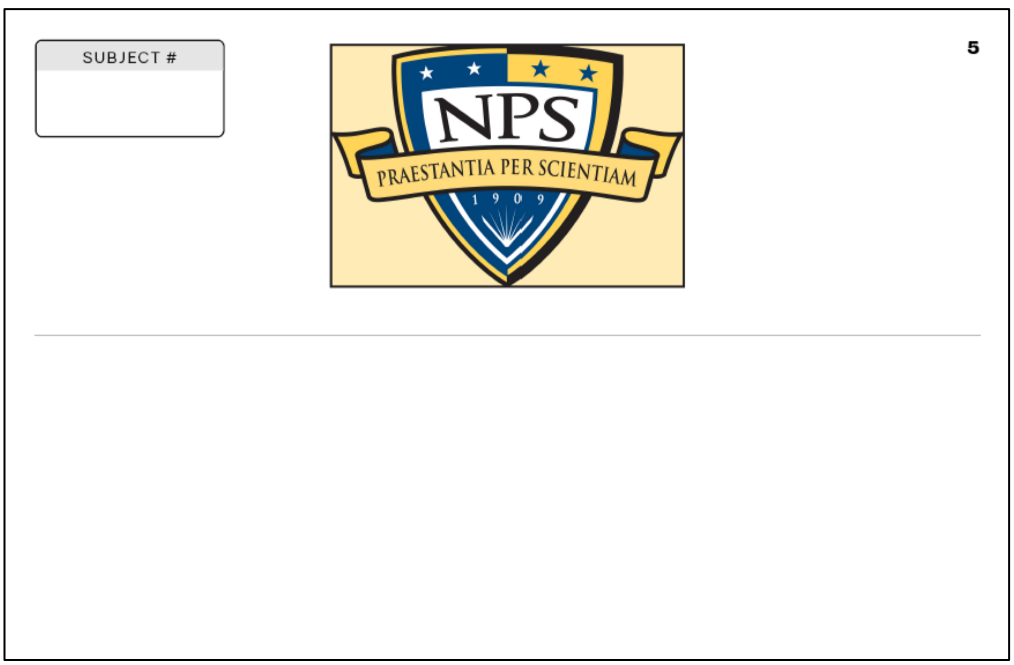


Figure 40. Workspace for Task 5. Source: (R. Lee, personal communication, March 23, 2018)

APPENDIX C. EXPERIMENT SCRIPT

A. BEGINNING SCRIPT

Thank you for volunteering to participate in this experiment. The experiment will take about one hour, but is not specifically bound by time. The experiment focuses on basic measurement and object orientation tasks performed through traditional methodology (a technical manual) and an augmented methodology (Microsoft HoloLens). Each methodology has a training session to ensure understanding that is open and not recorded. Questions are allowed during training. Once the experiment starts within each methodology, recording will begin, and very few questions are answerable. Be quick and precise with your actions.

In front of you is a consent form you can begin reading and need to sign to participate. This information will be secured during and after the experiment. We will be recording your session, but only the workspace - not your face. All personally identifiable information will be removed from the video to the maximum extent practical. If for any reason at any time you wish to be removed from the experiment, just ask and the experiment will terminate.

When you have completed the consent form please fill out the demographic survey. Upon completion we will begin the first training session.

Key words will be used in the experiment, “begin,” “complete,” “next,” “framed,” “reset,” “select.” During HoloLens use the preferred method of selection is spoken, but you can use either gesture or speech. This will be covered at the appropriate time.

Between each mini-session the experimenter will say “stand-by,” change the paper before you, and then say “when you are ready.” At that time, you may begin the next task. You don’t need to memorize these tasks, you will be reminded.

B. TECHNICAL MANUAL TRAINING SCRIPT

This training session is intended to familiarize you will the use of a ruler and a protractor. It is at your own pace and not recorded. The 11x17 paper before you is the workspace. The workspace paper may be written on in any manner you desire to help you complete the assigned task. Please take care of the manual, which is face down at this time to your left, and do not mark within it. You may place it in any location that best fits your needs without blocking the camera or your access to your parts. Parts will eventually be placed on the right side of the workspace.

When you are ready please turn over the manual and proceed.

*****<AT END OF TRAINING SESSION – MAX 30 MINS> “Do you feel able to use the ruler and protractor on your own,” IF NO: “We appreciate your time but we cannot include you within the study.” IF YES: We are now entering into the experiment, I will most likely not be able to answer questions. <**START CAMERA RECORDING**> When you are ready <**POINT AT MANUAL**>

C. MICROSOFT HOLOLENS TRAINING SCRIPT

This training session is intended to familiarize you with the use of Microsoft HoloLens™. It is at your own pace. You may repeat work as needed to become familiar. Let’s first cover the headset itself. In the back is a tightening/loosening dial. **<SHOW>**

Do not overtighten, I repeat, do not overtighten, it should just be enough where it does not feel like it is falling off/loose. When donning the headset ensure this portion of the headset **<POINT>** is roughly parallel to the ground. If you are wearing glasses you may gently pull the outer ring forward **<POINT>** to get the lenses of the headset in front of your glasses. All in all, the optics should be in front of your eyes with the nosepiece on your nose. If the headset is misaligned, when you look through the optics it will feel like you are looking up or down to see the middle of the optical field of view. The center of that field of view is a small white dot. The small white dot is surrounded by a halo effect when on menus. When the dot is over a button it is highlighted. Turning your head to place the white dot on a button, and then using a selection technique progresses you like a mouse and mouse button click would.

Now let's cover important HoloLens™ gestures. Consider gestures discrete actions. Being expressive will not help.

The area in front of you roughly bounded by your shoulder width and ¾ arm's length is a viable area for the HoloLens **<SHOW>**.

Using the area right in front of your eyes, while effective, is not necessarily optimal for hand movements **<SHOW>**.

The first gesture is called bloom. It is performed in two steps. Hand in cone shape facing up. Then slowly raise hand while opening coned fingers. **<SHOW>**

The next gesture is called a sky pinch. It is a way to select something similar to a mouse button click. Raise and hold open 'pinch' of forefinger and thumb for one second. Then close 'pinch' touching forefinger and thumb **<SHOW>.** Make sure you can see the pinch point of your fingers, if you cannot Microsoft can't either. <**SHOW BAD ONE, THEN GOOD ONE>**

We will use verbal commands with the HoloLens™. The word for sky pinch is 'SELECT'. It will select anything under the center white dot.

"Begin" will be used to start each task. Before you say begin, ensure you are comfortably seated and centered on the NPS graphic in the workspace. Stabilize your head movement as you say begin. Move freely after the graphic changes. "Complete" will be used to end each task. "Next" will be used to proceed to the next step in a task. Lastly a very important command is Reset. It will repeat a step. With all of these commands a 'sky pinch' button will be available if you so prefer.

Bear in mind when a 3D virtual object is presented before you, you are able to look around the object to get a 'better view'. **<SHOW>**

Are you ready to put on the headset? <**HELP PLACEMENT**> Be careful not to tighten too much. Can you see the white dot? <**LOOK AT SCREEN ON THE LAPTOP**>. Ok, let's do a bloom. Now move your head to place the white dot on the plus to the right. <**VERBALLY WALK THEM THERE**>. Sky pinch. Move your head to Calibration on the first row <**SAY SELECT**>. Please follow the prompting.

When complete: please bloom. Look at the plus sign. ‘Select’. Look at HoloLens assembly on the second column. ‘Select’. Look up. ‘Select’. <**DIRECT THEIR VISION TO THE NPS LOGO**>.

<**After they say begin and they are in process of placing the last object**>: As you can see the text box presents information to you that you can reference. The buttons on the bottom or side can be actioned verbally with their names, or you may sky pinch them. Any questions about that? Do not expect to the see the entire workspace at once. If you cannot see a portion of the workspace, look around or back up a bit. A stop sign image is to the left of the disc image and closer to you. Can you see it? Does it look like it is on top of the symbol? <**If they say yes and the placement of objects is way off redo calibration**>

Are you comfortable with what you have seen so far? <IF YES, TELL THEM TO VERBALLY ACTION THE ‘C’ WORD YOU SEE ON THE RED BUTTON>.

Stand-by. <**SET NEW PAGE DOWN> <START CAMERA RECORDING!!!**> <**SET PIECES TO PROPER LOCATION**> We are now entering into the experiment, I will most likely not be able to answer questions. When you are ready.

****<**SAY STAND-BY AFTER THEY SAY COMPLETE> <CHANGE THE PAPER> <SET PIECES TO PROPER LOCATION> <SAY WHEN YOU ARE READY**>.

D. ENDING SCRIPT

<**AFTER LAST TASK: STOP RECORDING> <PLACE SURVEY IN FRONT OF THEM>** Please take a few minutes and fill out the post-task survey. <**WHEN COMPLETE**> Thank you for your participation, Any Questions?

Place both surveys within folder. Reset experiment for next participant. Check time left on SD memory card. If less than 1.5 hours then replace with new one.

APPENDIX D. IMAGE CORRECTION

The thesis author conceptualized the image correction. A digital graphic designer developed the method using Adobe After Effects.

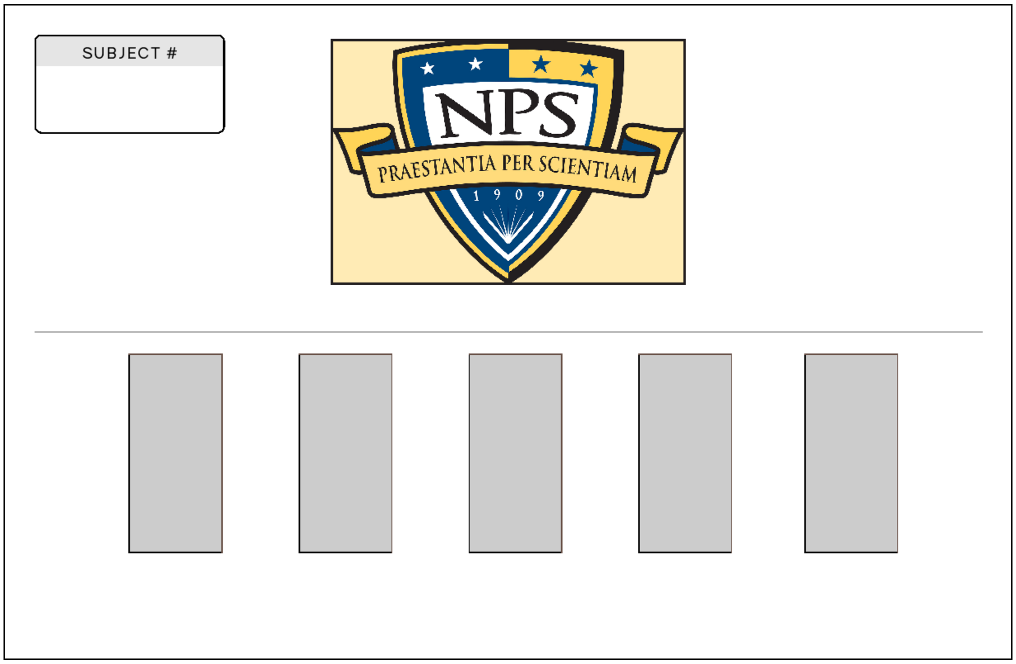


Figure 41. Image Correction Template for Tasks 1 and 3. Source: (R. Lee, personal communication, March 23, 2018)

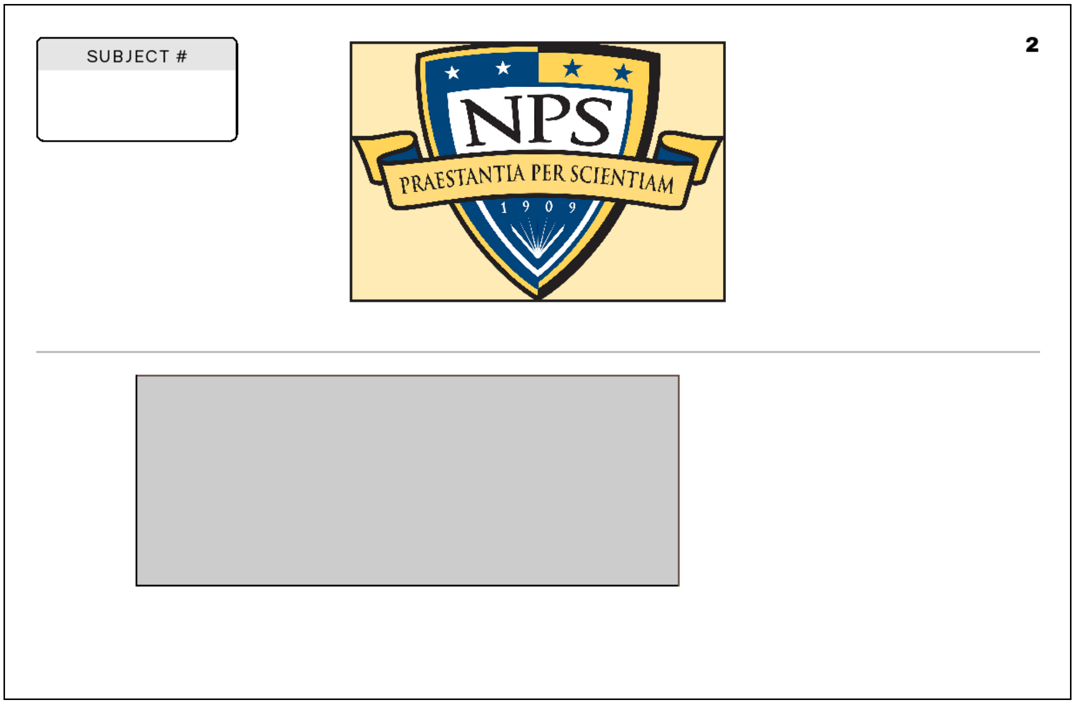


Figure 42. Image Correction Template for Task 2. Source: (R. Lee, personal communication, March 23, 2018)

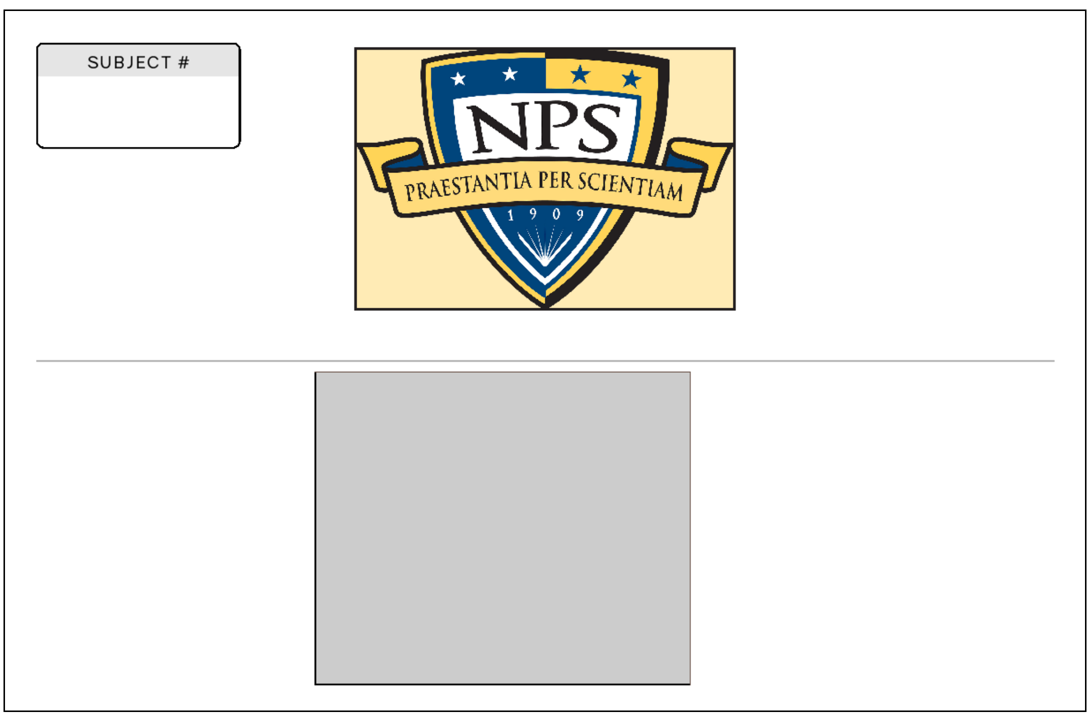


Figure 43. Image Correction Template for Task 4. Source: (R. Lee, personal communication, March 23, 2018)

Figure 44. Initial Part Placement within Template.

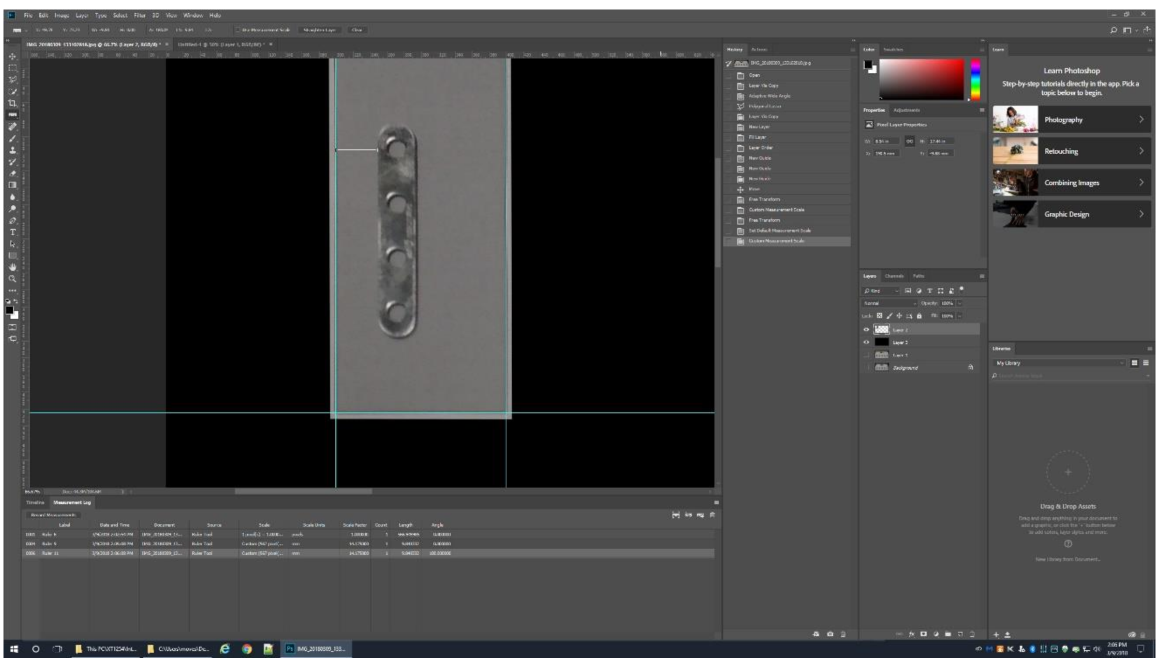


Figure 45. Top Horizontal Measurement after Image Correction. Source: (R. Lee, personal communication, March 9, 2018)

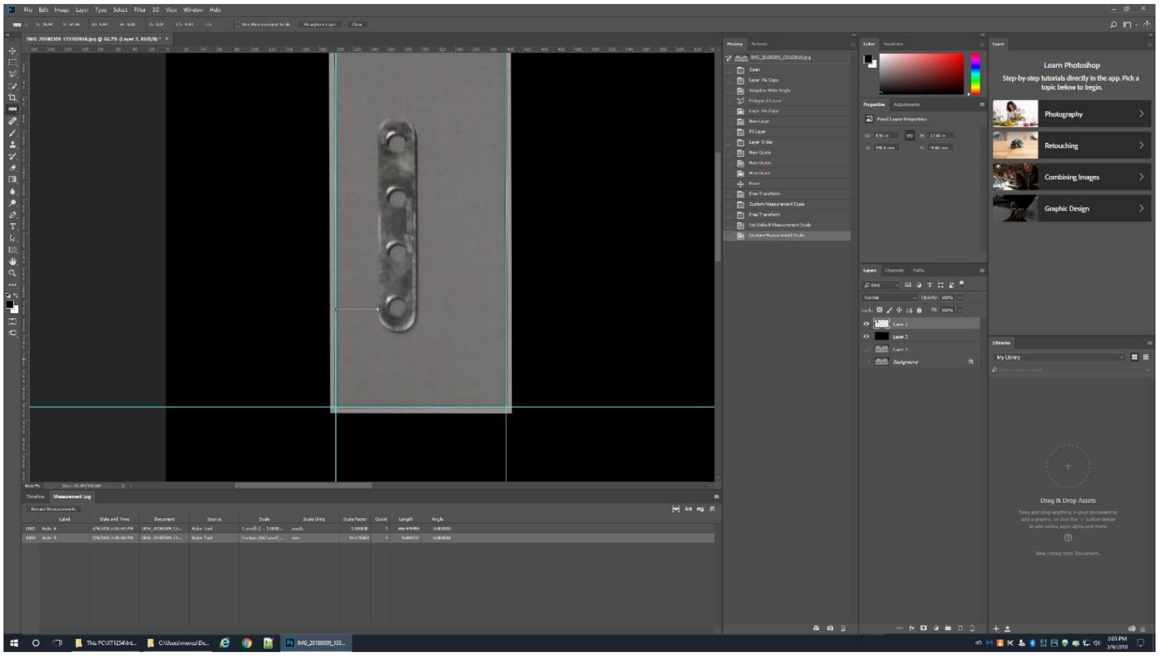


Figure 46. Bottom Horizontal Measurement after Image Correction. Source: (R. Lee, personal communication, March 9, 2018)

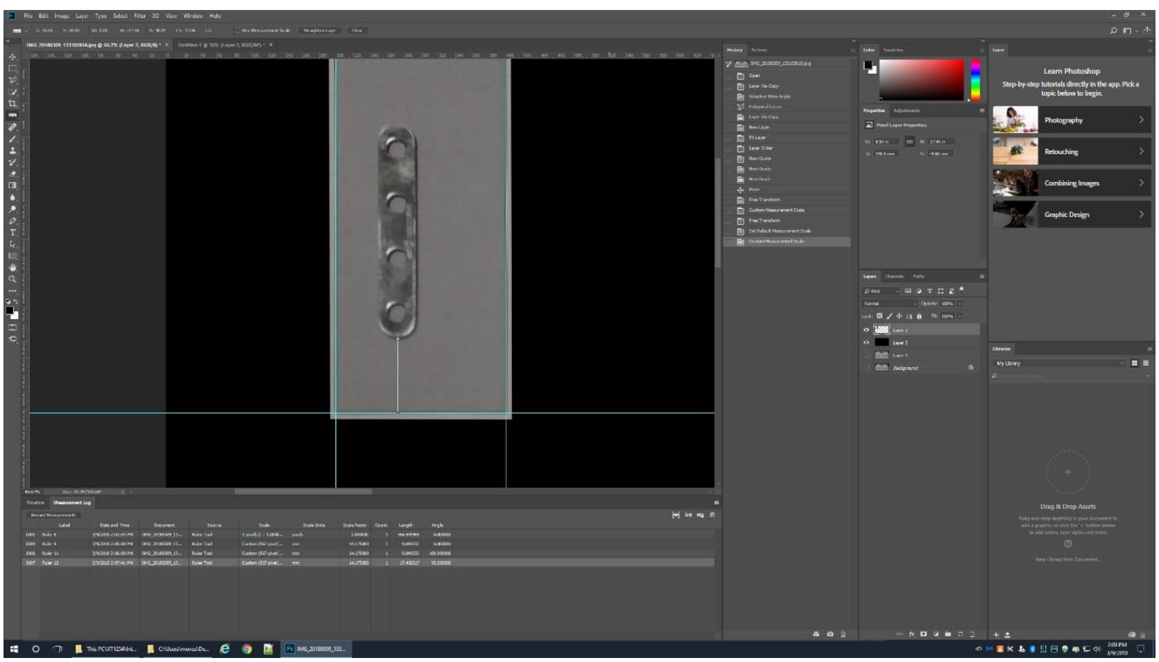


Figure 47. Vertical Measurement after Image Correction. Source: (R. Lee, personal communication, March 9, 2018)

APPENDIX E. PRECISION EVALUATION IMAGE

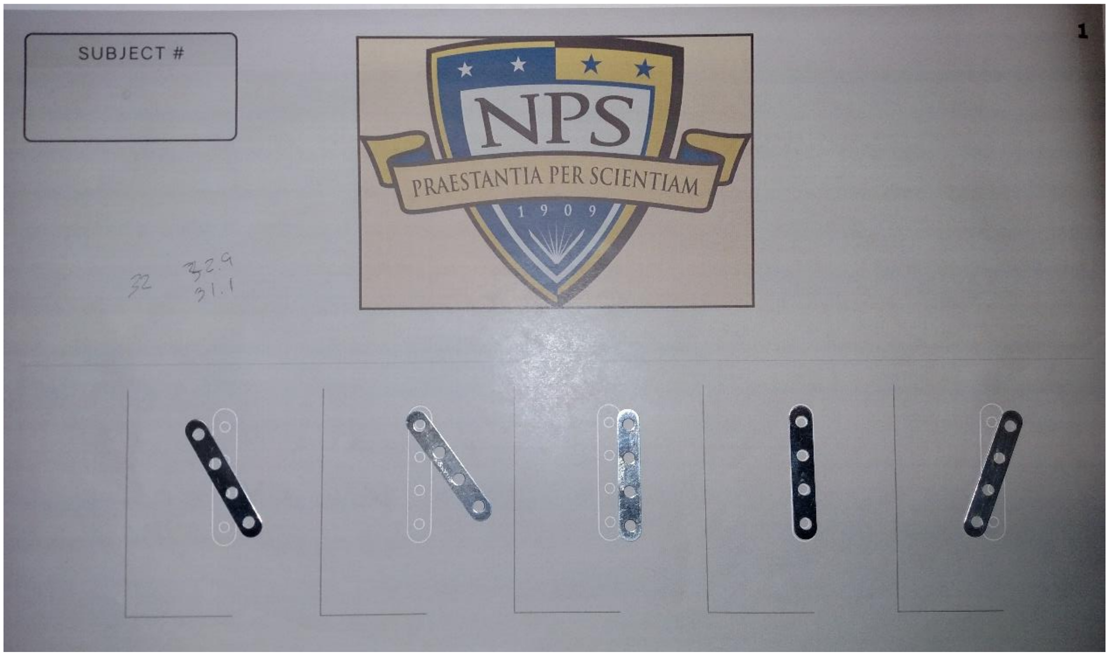


Figure 48. Precision Evaluation Image. Adapted from: (R. Lee, personal communication, April 23, 2018)

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APPENDIX F. O*NET ABILITIES AND SKILLS

The entirety of this appendix is verbatim from the website (“Browse by O*NET Data,” n.d.)

A. ABILITIES

1. Cognitive Abilities

Abilities that influence the acquisition and application of knowledge in problem solving

- CA1: Written comprehension - The ability to read and understand information and ideas presented in writing.
- CA2: Spatial orientation - The ability to know your location in relation to the environment or to know where other objects are in relation to you.
- CA3: Selective attention - The ability to concentrate on a task over a period of time without being distracted.
- CA4: Perceptual speed - The ability to quickly and accurately compare similarities and differences among sets of letters, numbers, objects, pictures, or patterns. The things to be compared may be presented at the same time or one after the other. This ability also includes comparing a presented object with a remembered object.
- CA5: Memorization - The ability to remember information such as words, numbers, pictures, and procedures.
- CA6: Mathematical reasoning - The ability to choose the right mathematical methods or formulas to solve a problem.
- CA7: Deductive reasoning - The ability to apply general rules to specific problems to produce answers that make sense.

- CA8: Time sharing - The ability to shift back and forth between two or more activities or sources of information (such as speech, sounds, touch, or other sources).

- CA9: Perceptual speed - The ability to quickly and accurately compare similarities and differences among sets of letters, numbers, objects, pictures, or patterns. The things to be compared may be presented at the same time or one after the other.

- CA10: Oral expression - The ability to communicate information and ideas in speaking so others will understand.

2. Physical Abilities

Abilities that influence strength, endurance, flexibility, balance and coordination

- PHA1: Extent flexibility - The ability to bend, stretch, twist, or reach with your body, arms, and/or legs.

3. Psychomotor Abilities

Abilities that influence the capacity to manipulate and control objects

- PSA1: Finger dexterity - The ability to make precisely coordinated movements of the fingers of one or both hands to grasp, manipulate, or assemble very small objects.

- PSA2: Manual dexterity - The ability to quickly move your hand, your hand together with your arm, or your two hands to grasp, manipulate, or assemble objects.

- PSA3: Multi-limb coordination - the ability to coordinate two or more limbs (for example, two arms, two legs, or one leg and one arm) while sitting, standing, or lying down. It does not involve performing the activities while the whole body is in motion.

4. Sensory Abilities

Abilities that influence visual, auditory and speech perception

- SA1: Depth perception - The ability to judge which of several objects is closer or farther away from you, or to judge the distance between you and an object.

- SA2: Near vision - The ability to see details at close range (within a few feet of the observer).

B. SKILLS

1. Basic Skills

Developed capacities that facilitate learning or the more rapid acquisition of knowledge

- BS1: Active learning - Understanding the implications of new information for both current and future problem-solving and decision-making.

- BS2: Monitoring - Monitoring/Assessing performance of yourself, other individuals, or organizations to make improvements or take corrective action.

2. Technical Skills

Developed capacities used to design, set-up, operate, and correct malfunctions involving application of machines or technological systems

- TS1: Quality control analysis - Conducting tests and inspections of products, services, or processes to evaluate quality or performance.

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APPENDIX G. TASK EXPECTED FINAL STATES

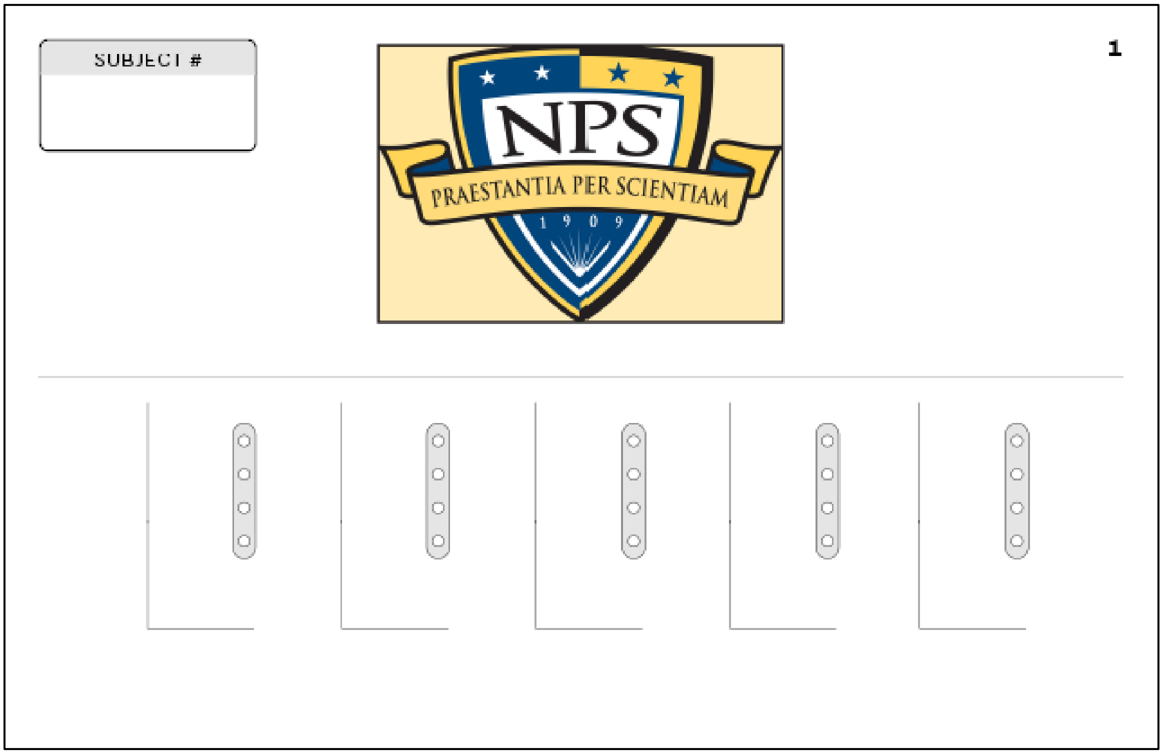

Figure 49. End State of Task 1. Source: (R. Lee, personal communication, March 23, 2018)

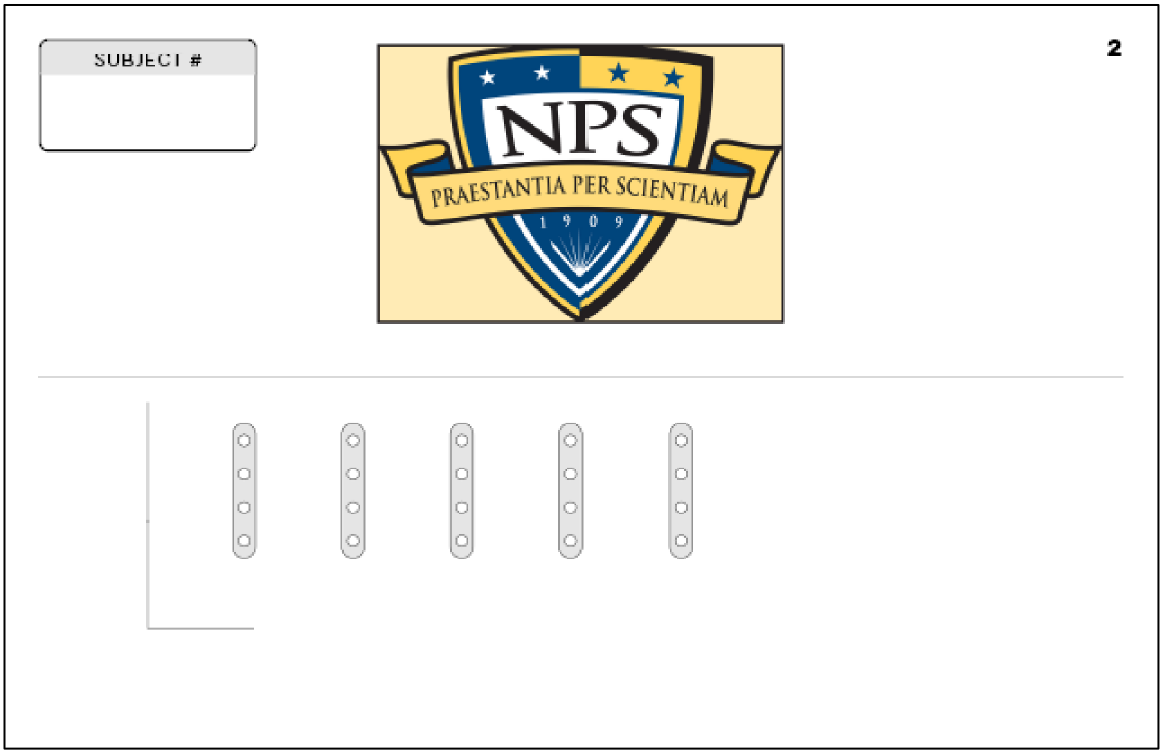

Figure 50. End State of Task 2. Source: (R. Lee, personal communication, March 23, 2018)

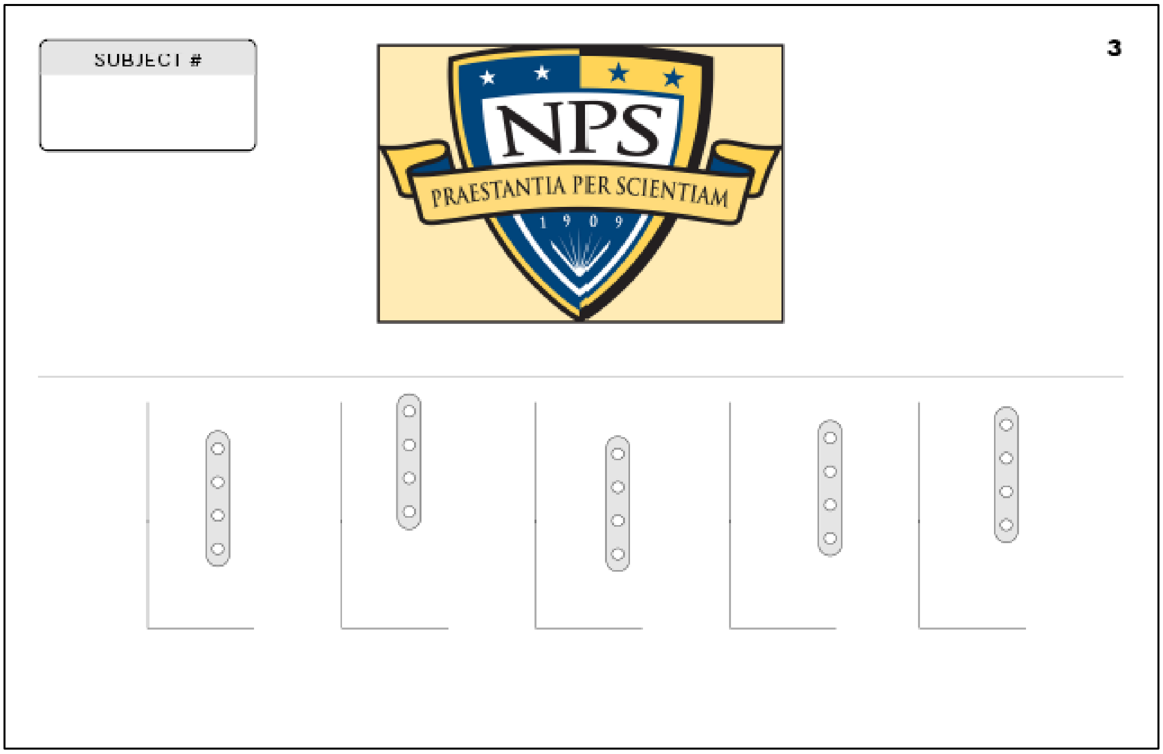

Figure 51. End State of Task 3. Source: (R. Lee, personal communication, March 23, 2018)

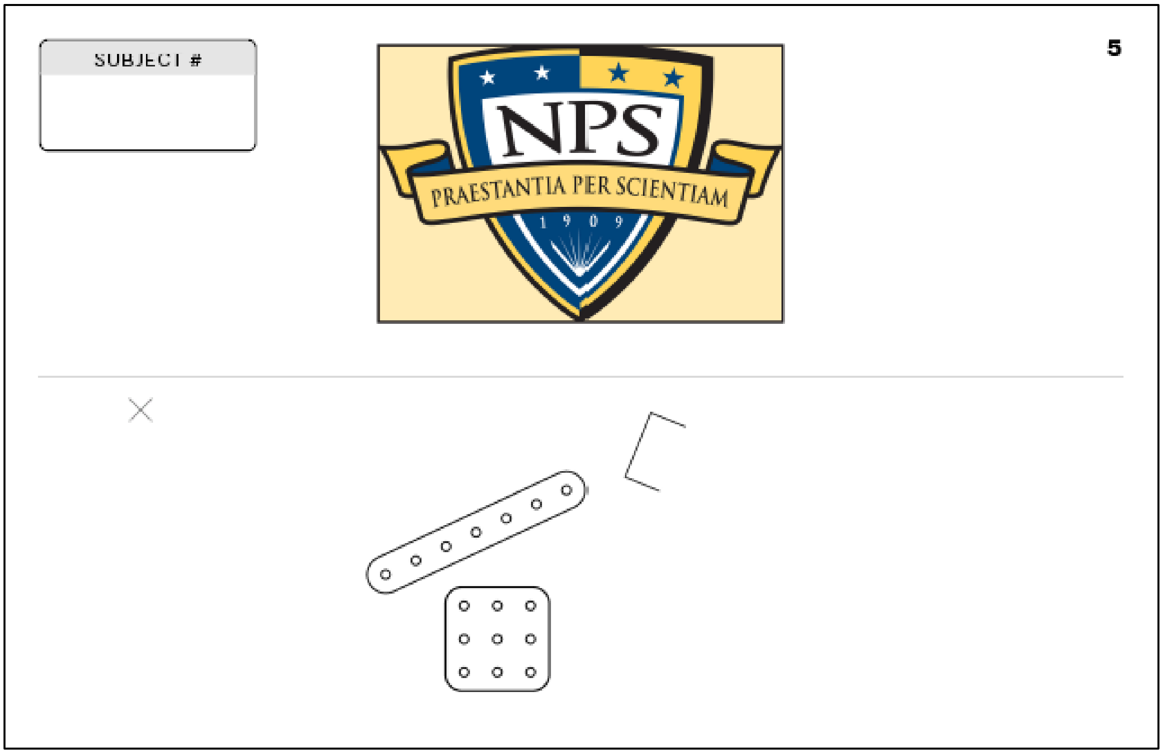

Figure 52. End State of Task 4. Source: (R. Lee, personal communication, March 23, 2018)

APPENDIX H. VIRTUAL OBJECT PLACEMENT

The following figures contain white outline virtual objects presented to the subject during the experiment from an orthogonal view of top down. Printed sheets enabled virtual object locations measured in the real world, which aligned per design specifications.

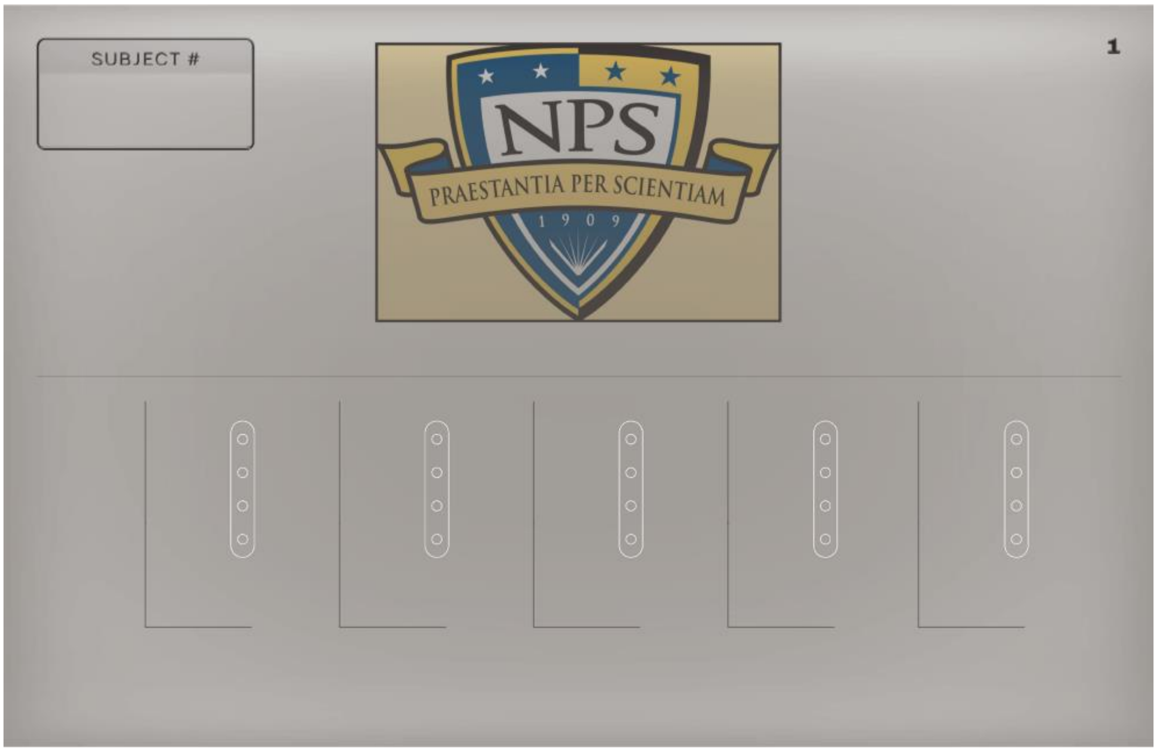

Figure 53. Virtual Object Guides for Task 1. Source: (R. Lee, personal communication, March 23, 2018)

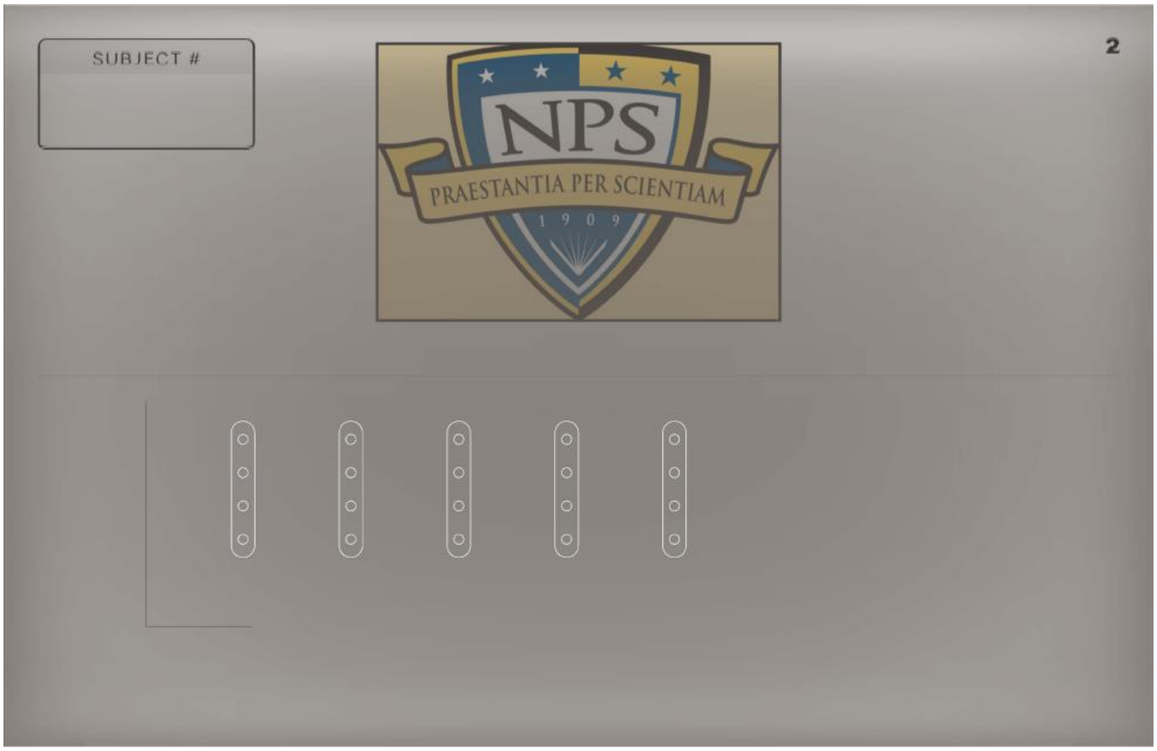

Figure 54. Virtual Object Guides for Task 2. Source: (R. Lee, personal communication, March 23, 2018)

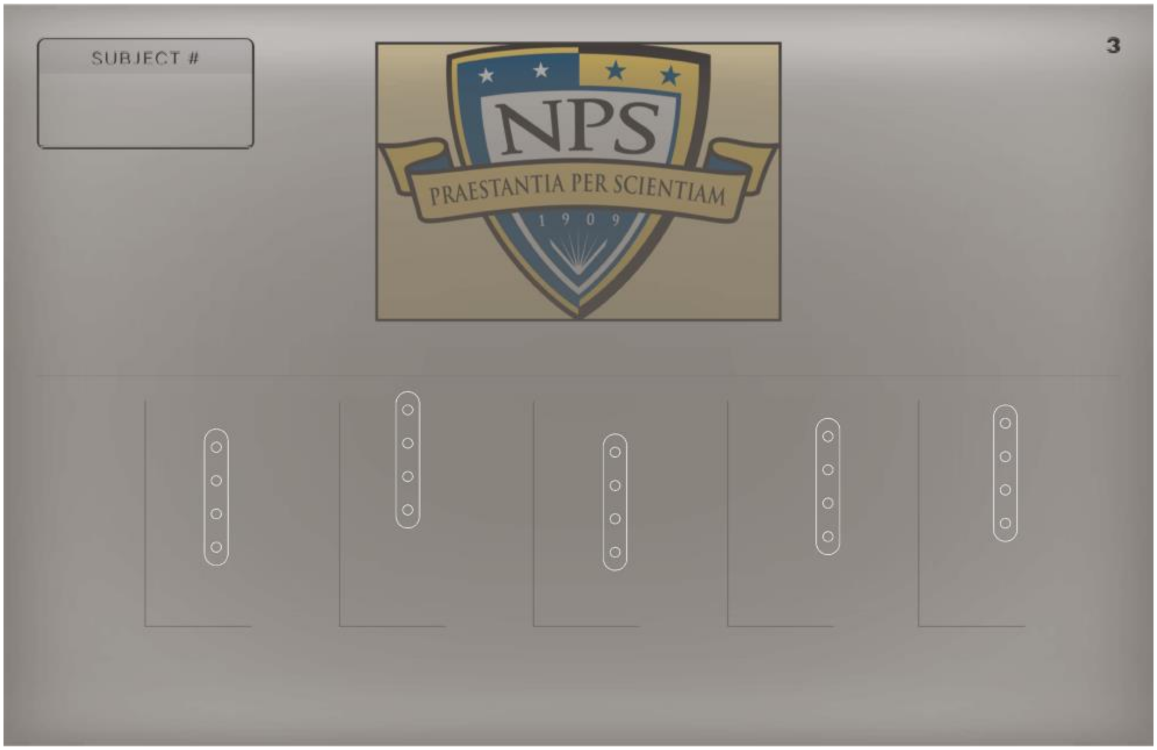

Figure 55. Virtual Object Guides for Task 3. Source: (R. Lee, personal communication, March 23, 2018)

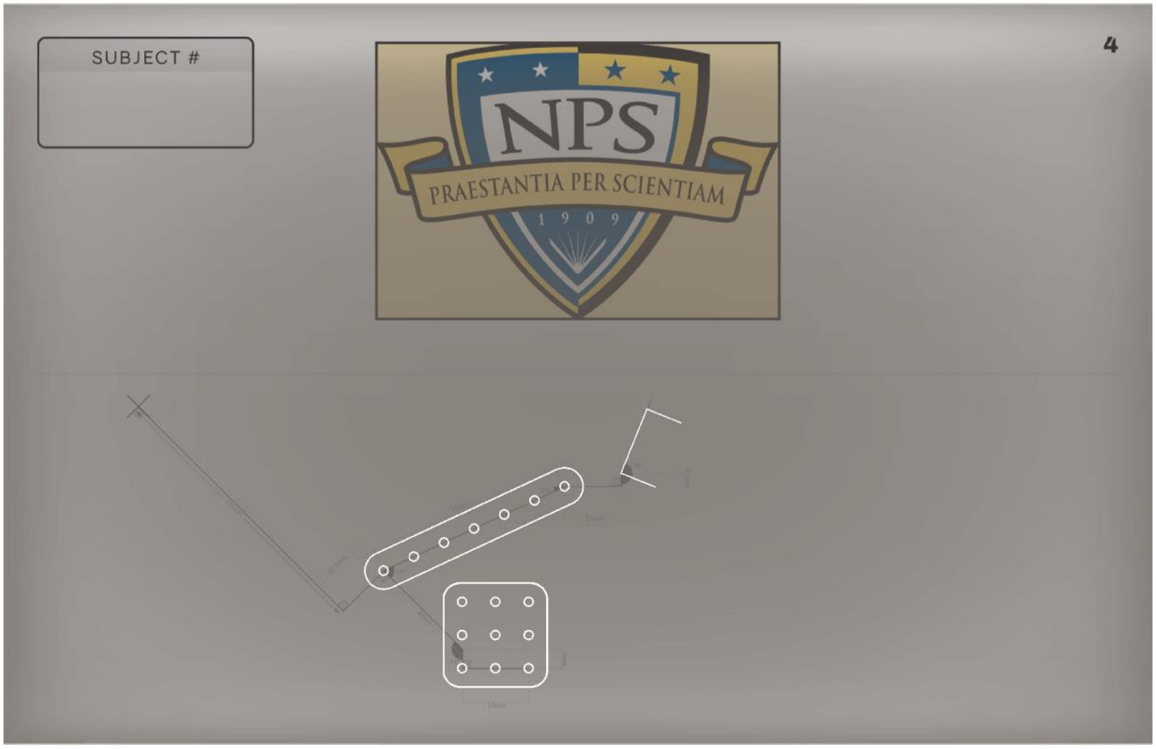

Figure 56. Virtual Object Guides for Task 4. Source: (R. Lee, personal communication, March 23, 2018)

APPENDIX I. OUTLIER DATA

Figures 57 through 63 depict raw data before removal of outliers.

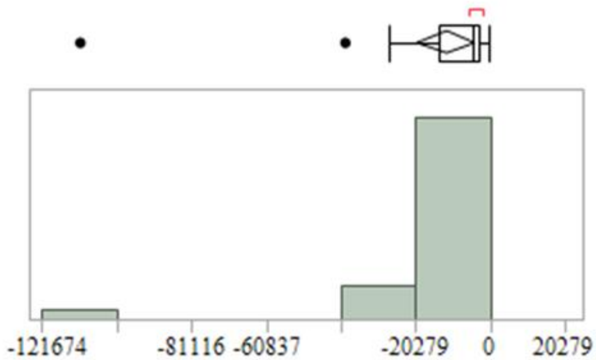

Figure 57. Efficiency: Absolute Error Original Histogram of Figure 6.
$3*IQR = 31733.7$

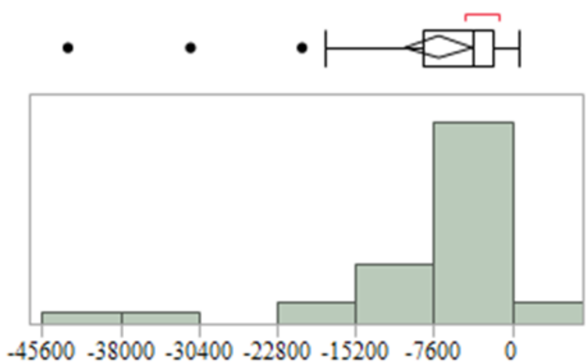

Figure 58. Efficiency: Absolute Referential Error Original Histogram of Figure 10
$3*IQR = 20254.59$

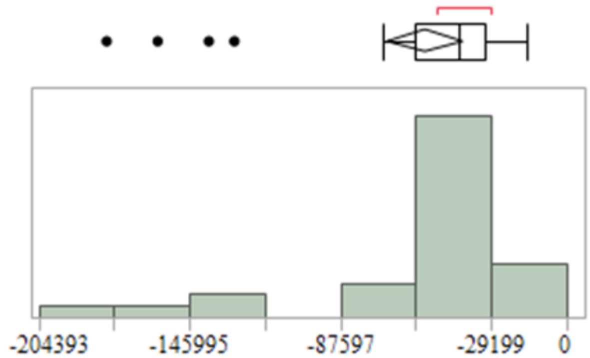

Figure 59. Efficiency: Complexity Error Original Histogram of Figure 12 $3*IQR = 80232.87$

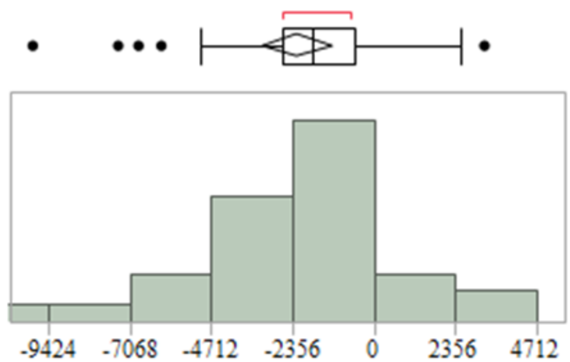

Figure 60. Efficiency: Complexity Error (Placement Only) Original Histogram of Figure 14 $3*IQR = 6301.35$

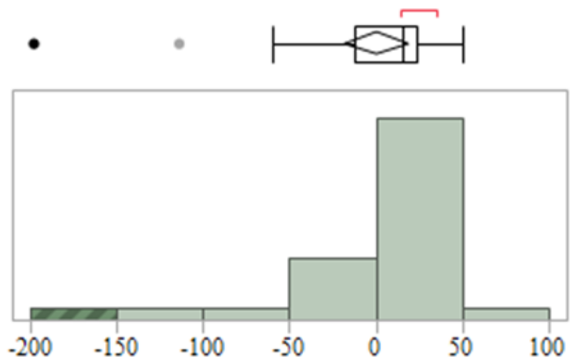

Figure 61. Precision: Absolute Error Original Histogram of Figure 18 $3 * IQR = 110.31$

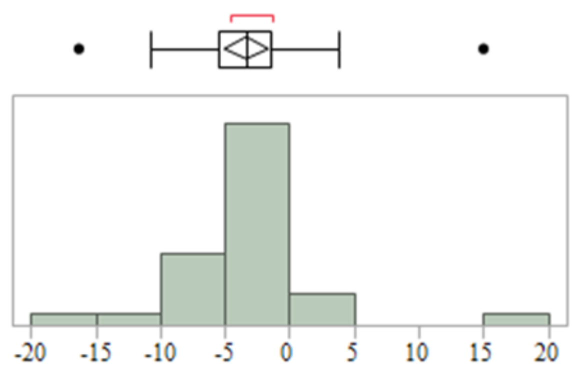

Figure 62. Time: Long Part Original Histogram of Figure 28 $3 * IQR = 12.06$

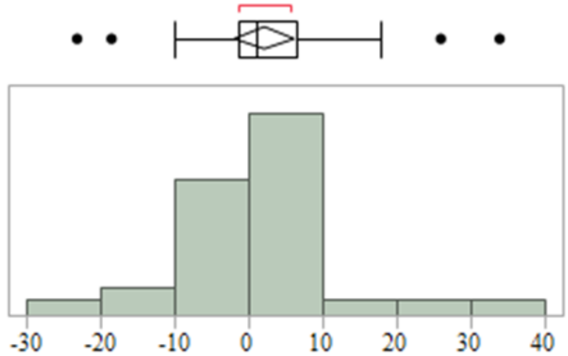

Figure 63. Time: C Part Original Histogram of Figure 32 $3*IQR = 23.9$

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